ENVIRONMENT MEASUREMENT METHODS, SYSTEMS, MEDIA, SIGNALS AND DATA STRUCTURES

BACKGROUND OF THE INVENTION

1. Field of Invention

The present invention relates to measurement, and more particularly, to environment measurement methods, systems, media, signals and data structures.

2. Description of Related Art

Environment measurement systems have many useful applications. For example, forestry companies often require reasonably accurate surveys of ground elevation and foliage height in a given area of the environment, in order to determine how best to build access roads and carry out forestry practices in the area. Similarly, many other types of businesses, as well as governmental bodies, particularly those involved in management of agriculture, forests or natural resources, often require surveys of at least terrain height in a given area. In addition to ground elevation and foliage height, many entities, such as oil and gas exploration companies for example, often wish to obtain information about subterranean strata, objects, or other underground aspects of the environment, if possible.

One existing environment measurement method involves the use of radar. For example, an incident radar beam may be directed from an aircraft to the environment. The radar beam is then reflected or scattered by the environment back to the aircraft, where it is detected at a detector. The signals produced by

the detector may then be used to produce information about the environment beneath the aircraft.

However, existing radar systems suffer from a number of limitations. For example, radar systems typically have low resolution, or in other words, they are typically poor at distinguishing between nearby objects emitting similar energy levels. Thus, typical existing radar systems are not reliably accurate in measuring smaller objects, such as measuring radar return scattered by treetops to determine foliage height, for example. Radar representations are also subject to geometric distortions due to rapid relief changes in the object being measured. In addition, many existing radar systems employ wavelengths less than **0.1** meters, and often less than **0.01** meters, however, such wavelengths generally provide little or no subterranean penetration, and indeed, frequently fail to penetrate thick foliage to reach the ground and back.

Another type of environment measurement system includes light detection and ranging (lidar) systems, which use a laser to direct a laser beam to the environment, and a detector the aircraft for determining the distance to the environment in response to the return travel time of the laser beam to the environment and back. Laser systems are typically capable of producing appreciably more accurate measurements of distances to small objects, and are therefore capable of providing more accurate foliage height measurements than typical radar systems. However, in light to moderate foliage thicknesses, the laser beam often cannot penetrate through the foliage to the ground and back. Thus, the laser systems, although more accurate in some respects, are limited in the information they can provide in many circumstances. In addition, existing laser systems typically produce data only in response to the first and last returns from the environment (such as returns from a highest treetop and from the ground, for example), and do not make use of laser returns from portions of the environment in between (such as

intervening foliage, twigs or branches, for example). In addition, laser systems are generally not capable of providing subterranean information, and indeed, frequently do not even detect the ground surface.

Accordingly, there is a need for an improved environment measurement system.

SUMMARY OF THE INVENTION

The present invention addresses the above need by providing, in accordance with a first aspect of the invention, an environment measurement method. The method includes receiving first signals produced in response to a laser beam scattered by the environment, receiving second signals produced in response to a radar beam scattered by the environment, and storing data representing the first and second signals, for use in producing a representation of the environment.

Thus, data for use in producing a representation of the environment may be stored in response to both laser and radar signals, thereby overcoming the disadvantages associated with either type of measurement device by itself. For example, the greater resolution of laser measurements for determining foliage height, along with the lack of susceptibility of such laser measurements to either geometric distortions or to constructive or destructive interference, may be combined with the ability of radar to identify ground height even in thick foliage conditions. In this regard, if desired, a relative foliage height of the environment may be determined, by subtracting a ground level height obtained from radar data, from an absolute foliage height value obtained from laser data. Alternatively, the two types of data may be combined in other ways to form other types of unitary representations, such

as by using laser data corresponding to ground returns to arbitrate or calibrate the radar data, for example.

The method may involve receiving the laser beam scattered by the environment and producing the first signals in response thereto. The method may further involve producing an incident laser beam for scattering by the environment to produce the laser beam scattered by the environment.

The method may involve directing the incident laser beam to the environment at a desired angle. In this regard, directing may include adjusting a physical orientation of a beam directing device in response to an orientation signal, to direct the incident laser beam to the environment at the desired angle. The method may also involve producing the orientation signal. Likewise, the method may involve directing the laser beam scattered by the environment from the beam directing device to a detector.

Receiving the laser beam scattered by the environment may include receiving scattered portions of a laser pulse scattered by respective portions of the environment. Similarly, producing the first signals may further include continuously producing data signals in response to the scattered portions of the laser pulse, during a measurement interval of sufficient duration to receive all the scattered portions.

The method may further involve producing the second signals in response to a radar beam scattered by the environment.

In this regard, the method may involve receiving the radar beam scattered by the environment at an airborne receiver, the radar beam having a wavelength of at least on the order of one meter. For example, this may involve receiving, as the radar beam scattered by the environment, a radar beam having a wavelength between **0.7** and **2** meters.

Similarly, the method may include directing an incident radar beam to the environment to produce the radar beam scattered by the environment. This may entail directing to the environment, as the incident radar beam, an ultra-wide band (UWB) radar beam.

Directing may include transmitting the incident radar beam to the environment from a transmission antenna system, and the method may further involve receiving the radar beam scattered by the environment at a reception antenna system.

Producing the second signals may involve delaying signals produced by at least some of a plurality of antennae of the reception antenna system.

The transmission antenna system and the reception antenna system may include a common transceiving antenna system, and transmitting and receiving may thus include transmitting and receiving at the common transceiving antenna system. Alternatively, however, separate antenna systems may be employed for transmitting and receiving.

The method may further include blanking transmitter cross-talk signals while directing the incident radar beam to the environment.

Producing the second signals may include producing frequency-shifted signals in response to the radar beam scattered by the environment. Producing the frequency-shifted signals may involve producing initial electrical signals at frequencies of the radar beam scattered by the environment, in response thereto, and may further involve applying the initial electrical signals and a mixing frequency signal to a mixer, to produce the frequency-shifted signals. Alternatively, or in addition, producing frequency-shifted signals may involve producing in-phase frequency-shifted signals and in-quadrature

frequency-shifted signals. Producing the second signals may further include digitizing the frequency-shifted signals.

The method may also involve adjustably attenuating the second signals.

Storing the data may include defining a data structure including a measurement context field for storing measurement context information, a laser field for storing the data representing the first signals, and a radar beam field for storing the data representing the second signals.

Similarly, storing the data may involve storing measurement context information in association with the data representing the first and second signals. In this regard, the measurement context information may include global positioning satellite (GPS) information indicative of a location at which at least one of the laser beam and the radar beam is received, at least one time value indicative of a time at which at least one of the laser beam and the radar beam is received, attenuation information indicative of an amount of attenuation of the second signals, a frequency value indicative of a frequency of the radar beam, user-inputted information, or a flight line indication indicative of a flight line over which the laser beam and the radar beam are received by an airborne environment measurement system, or any combination thereof, for example.

Storing the data representing the second signals may involve storing an in-phase value and an in-quadrature value representing an in-phase component and an in-quadrature component respectively of the second signals.

The method may also involve producing the representation of the environment in response to the data. In this regard, producing the representation may involve applying a migration algorithm to the data representing the second signals, to associate the data representing the second signals with particular

locations of the environment. Alternatively, or in addition, producing the representation may include identifying a foliage height of the environment, identifying a height of a terrain surface of the environment, identifying features of the environment below the terrain surface, identifying a slope of the terrain surface, producing a digital elevation model of the environment, or producing at least one contour representation of the environment, for example.

In accordance with another aspect of the invention, there is provided an environment measurement system including a memory device and a processor circuit. The processor circuit is in communication with the memory device, and is configured to receive first signals produced in response to a laser beam scattered by the environment, to receive second signals produced in response to a radar beam scattered by the environment, and to store data representing the first and second signals in the memory device, for use in producing a representation of the environment.

If desired, the system may further include additional structural elements, such as elements described in greater detail herein for example, operable to perform various aspects of the methods described herein.

In accordance with another aspect of the invention, there is provided a data structure including a laser field for storing data representing first signals produced in response to a laser beam scattered by an environment, and a radar beam field for storing data representing second signals produced in response to a radar beam scattered by the environment.

In accordance with yet another aspect of the invention, there is provided an environment measurement method involving continuously producing data in response to scattered portions of a laser pulse scattered by respective portions of the environment, during a measurement interval of sufficient

duration to receive all the scattered portions, and storing the data, for use in producing a representation of the environment.

Thus, a full set of laser data, rather than merely a first return value, may be obtained for a given laser pulse. This may be particularly advantageous in light foliage conditions, for example, in which case the laser data may include not only a foliage height value, but also a ground height value, as well as one or more intermediate return values corresponding to objects such as foliage at intermediate heights between the foliage height and the ground height.

Such a measurement interval may be at least on the order of one microsecond, for example.

The method may further involve producing an incident laser pulse having a duration on the order of one nanosecond, for scattering by the environment to produce the scattered portions of the laser pulse.

The method may also involve receiving the incident laser pulse at a beam directing device, adjusting a physical orientation of the beam directing device in response to an orientation signal, to direct the incident laser pulse from the beam directing device to the environment.

In accordance with another aspect of the invention, there is provided an environment measurement system including a memory device and a processor circuit in communication with the memory device. The processor circuit is configured to cooperate with a detection system to continuously produce data in response to scattered portions of a laser pulse scattered by respective portions of the environment, during a measurement interval of sufficient duration to receive all the scattered portions, and to store the data in the memory device, for use in producing a representation of the environment.

If desired, the system may further include additional structural elements, such as elements described in greater detail herein for example, operable to perform various aspects of the methods described herein.

In accordance with another aspect of the invention, there is provided an environment measurement method, involving producing signals in response to a radar beam scattered by the environment and received at an airborne receiver, the radar beam having a wavelength of at least on the order of one meter. The method further includes storing data representing the signals, for use in producing a representation of the environment.

By employing a radar beam having a wavelength at least on the order of one meter, a number of advantages may be obtained. For example, 1-m wavelengths typically penetrate relatively deep into soil, even moist soil, and therefore, data representing signals produced in response to such wavelengths may be used to produce a representation of a subterranean region of the environment. In addition, wavelengths between 0.75 m and 1.5 m are often reserved by governments as communications channels, and therefore, there is typically much less background noise in this wavelength range than in surrounding wavelength ranges, allowing for more accurate radar measurements with higher signal-to-noise ratios. Conversely, it should typically be possible to use this wavelength range with insufficient power to cause any significant long-range interference.

The method may further involve receiving the radar beam scattered by the environment at the airborne receiver, the radar beam having a wavelength between 0.7 and 2 meters.

Producing the signals may involve continuously producing data signals in response to scattered portions of a radar pulse scattered by respective

portions of the environment, during a measurement interval of sufficient duration to receive all the scattered portions.

The method may entail directing an ultra-wide band (UWB) incident radar beam to the environment to produce the radar beam scattered by the environment.

In accordance with another aspect of the invention, there is provided an environment measurement system including and airborne radar reception system and a processor circuit. The airborne radar reception system is operable to produce signals in response to a radar beam scattered by the environment and having a wavelength of at least on the order of one meter. The processor circuit is in communication with the airborne radar reception system, and is configured to store data representing the signals, for use in producing a representation of the environment.

In accordance with another aspect of the invention, there is provided an environment measurement method, involving receiving data representing signals produced at an airborne receiver in response to a radar beam scattered by the environment, and applying a migration algorithm to the data, to associate the data with particular locations of the environment.

In this regard, by applying a migration algorithm to the data, the effective spot size of the incident radar beam may be effectively decreased through integration, thereby improving the resolution of a resulting representation of the environment.

Similarly, In accordance with another aspect of the invention, there is provided an environment measurement system including a processor circuit configured to receive the data and apply the migration algorithm thereto.

In accordance with other aspects of the invention, there are provided environment measurement systems, each system including provisions for performing the functions of a respective one of the methods described above.

In accordance with other aspects of the invention, there are provided computer-readable media, each such medium storing codes for directing a processor circuit to perform the functions of a respective one of the methods described above.

In accordance with other aspects of the invention, there are provided signals, each such signal including code segments for directing a processor circuit to perform the functions of a respective one of the methods described above.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate embodiments of the invention,

Figure **1** is a block diagram of an environment measurement system according to a first embodiment of the invention, with an exemplary environment shown for illustrative purposes;

Figure **2** is a block diagram of an environment measurement system according to a second embodiment of the invention;

Figure **3** is a perspective view of the environment measurement system shown in Figure **2**, installed on an airborne vehicle;

Figure **4** is a cross-sectional view of an environment being measured by the system shown in Figures **2** and **3**, along with graphical representations of signals produced in response to a laser beam and a radar beam scattered by the environment;

Figure **5** is a block diagram of a laser system of the environment measurement system shown in Figure **2**;

Figure **6** is a block diagram of a radar transmission system of the environment measurement system shown in Figure **2**;

Figure **7** is a block diagram of a radar reception system of the environment measurement system shown in Figure **2**;

Figures **8a** and **8b** are a block diagram of a central processing system and a memory device of the environment measurement system shown in Figure **2**;

Figure **9** is a flowchart of a measurement routine executed by a processor circuit of the system shown in Figure **2**;

Figure **10** is a timing diagram of control signals produced by the system shown in Figure **2**, while executing the measurement routine shown in Figure **9**;

Figure **11** is a fragmented cross-sectional view of a second environment being measured by the system shown in Figure **2**, along with a graphical representation of signals produced in response to scattered portions of a laser pulse scattered by respective portions of the environment;

Figure **12** is a flowchart of an analysis routine executed by a representation processing circuit such as the processor circuit of the system shown in Figure **2**;

Figure **13** is a graphical illustration of a flight line representation which may be produced by the representation processing circuit while executing the analysis routine shown in Figure **12**;

Figure **14** is a graphical representation of a subterranean portion of the environment, which may be produced by the representation processing circuit while executing the analysis routine shown in Figure **12**;

Figure **15** is a contour representation of the environment, which may be produced by the representation processing circuit while executing the analysis routine shown in Figure **12**;

Figure **16** is a three-dimensional contour representation of the environment, which may be produced by the representation processing circuit while executing the analysis routine shown in Figure **12**;

Figure **17** is a block diagram of a radar transmission system according to a third embodiment of the invention; and

Figure **18** is a block diagram of a radar transceiving system according to a fourth embodiment of the invention.

DETAILED DESCRIPTION

Referring to Figure **1**, an environment measurement system according to a first embodiment of the invention is shown generally at **30**. The system **30** includes a memory device **32**, and a processor circuit **34** in communication with the memory device **32**. In this embodiment, the processor circuit **34** is configured to receive first signals **36** produced in response to a laser beam **38** scattered by the environment, to receive second signals **40** produced in response to a radar beam **42** scattered by the environment, and to store data **44** representing the first and second signals **36** and **40** in the memory device **32**, for use in producing a representation of the environment.

System

Referring to Figure **2**, an environment measurement system according to a second embodiment of the invention is shown generally at **50**. The system **50** includes a memory device shown generally at **52**, and a processor circuit shown generally at **54**, in communication with the memory device **52**. In this embodiment the processor circuit **54** is configured to receive first signals **56** produced in response to a laser beam scattered by the environment, to receive second signals shown generally at **58** produced in response to a radar beam scattered by the environment, and to store data representing the first and second signals **56** and **58** in the memory device **52**, for use in producing a representation of the environment.

More particularly, in this embodiment the system **50** includes a central processing system (CPS) shown generally at **60**, which in this embodiment includes the processor circuit **54**.

In the present embodiment the central processing system (CPS) **60** is in communication with a laser system shown generally at **62**, and with a radar system shown generally at **64**.

In this embodiment the radar system **64** includes a radar transmission system **66**, a radar reception system **68**, and a power supply system **70**. In this embodiment the power supply system **70** receives unregulated aircraft direct current (DC) power, in response to which it produces and supplies regulated direct current (DC) power to the various components of the radar system **64**. More particularly, in the present embodiment the power supply system **70** produces regulated direct currents of **5** amps at **+5** volts, **1** A @ **+15** V and **1** A at **-15** V, which are then supplied to appropriate components of the radar system **64**.

In this embodiment, the power supply system **70** includes an analog DC power supply **72**, which tends to produce less broad-band noise than comparable digital power supplies. Accordingly, additional radio frequency interference (RFI) filtration of the incoming power is not required in the present embodiment. Alternatively, however, other types of power supplies may be substituted, although an appropriate RFI filter (not shown) may be required in such alternative embodiments depending on the amount of noise produced by the power supply.

If AC power is not available in a particular embodiment, then the power supply system **70** may further include power inverters to produce regulated **115** V AC power from an available DC power supply (such as a **28** V DC power supply available on many aircraft, for example). Each inverter may include a suitable breaker, such as a **50** amp breaker, for example.

In this embodiment the CPS **60** is in further communication with a global positioning system (GPS) device **80**. The GPS device receives navigation

(NAV) message signals from a plurality of GPS satellites orbiting the earth, in response to which it produces data signals indicating the position and velocity of the GPS device, and also the present time. In this embodiment the GPS provides updated data signals representing such information twice per second, although alternatively, faster or slower updating rates may be used. In the present embodiment the GPS device is the sole GPS receiver employed by the system **50**. Alternatively, however, if desired, accuracy of the GPS device **80** may be further improved through differential positioning (DGPS). For example, a second GPS receiver (not shown) may be provided at a nearby known location, to allow for determination of a GPS positioning error and calculation of a corresponding corrective factor to be applied to the position data produced by the GPS device **80**.

In the present embodiment the CPS **60** is also in communication with further input/output devices, including a manual input device **90**, a camera **92** and a display device **94**. In this embodiment the manual input device **90** includes a keyboard, and the camera **92** includes a Kodak Professional DCS-**460** Digital Camera.

Airborne System

Referring to Figures **2**, **3** and **4**, in the present embodiment the system **50** is mountable in an aircraft, such as that shown at **100** in Figure **3**. More particularly, in the present embodiment the aircraft **100** is a Beechcraft Super Kingair **200** airplane. Alternatively, however, the system **50** may be employed with other types of aircraft such as other airplanes or helicopters for example, or may be employed in other contexts if desired.

Thus, in this embodiment the system **50** includes the radar system **64**, which is operable to produce the second signals **58** in response to a radar beam scattered by the environment. More particularly, in this embodiment the radar

system **64** is configured to direct an incident radar beam, shown generally at **102** in Figures **3** and **4**, to the environment, which is shown generally at **104** in Figure **4**, to produce the radar beam scattered by the environment, shown generally at **106** in Figure **3**.

More particularly still, in this embodiment the radar system **64** includes a transmission antenna system shown generally at **108** in Figure **3**, which is configured to direct the incident radar beam **102** to the environment **104**, and a reception antenna system shown generally at **110**, configured to receive the radar beam **106** scattered by the environment **104**.

Similarly, in this embodiment, the laser system **62** directs an incident laser beam **112** to the environment **104**, which scatters the incident laser beam **112**, or in other words, produces a laser beam scattered by the environment such as that shown generally at **114** in Figure **3**.

Laser System

Referring to Figures **2**, **3**, **4** and **5**, the laser system of the present embodiment is shown generally at **62** in Figure **5**. In this embodiment the laser system **62** includes a laser **120** operable to produce the incident laser beam **112**, for scattering by the environment **104** to produce the laser beam **114** scattered by the environment.

More particularly, in this embodiment the laser **120** includes a laser manufactured by Riegl Laser Measurement Systems GmbH of Horn, Austria as a component of Riegl Laser Mirror Scanner LMS-Q**140**i-**60/80**. In the present embodiment the laser **120** is operable to produce, as the incident laser beam **112**, a laser pulse at a near-infrared wavelength of **900** nanometers, having a pulse duration of approximately **2** nanoseconds and a beam divergence of **3** milliradians. In this embodiment the laser **120**

produces such a pulse every **1** / **75**th of a second, or in other words, is operated at a pulse repetition rate of **75** Hz. The incident laser beam **112** produced by the laser **120** has a Class **1** eye safety, and therefore minimizes safety risks to any humans or animals in the environment **104** or aboard the aircraft **100**.

Alternatively, however, other lasers may be substituted if desired. Generally, it is desirable that the laser **120** have a pulse repetition rate of at least about **60** Hz, and a signal-to-noise ratio of **0** dB or better for a **20**% reflective target (single pulse). It is also desirable for the laser **120** to be able to operate in altitudes between **1000** and **3000** feet AGL, even more preferably between **500** and **6000** feet AGL, to produce a spot size of **2** m diameter or smaller at **3000** feet AGL, and to have sufficient power to yield detectable scattered returns from low-reflectivity ground at flight altitude.

In this embodiment, the laser system **62** further includes a detector **122** operable to receive the laser beam **114** scattered by the environment **104** and to produce the first signals **56** in response thereto. More particularly, in this embodiment the detector **122** includes a detector manufactured and sold as a component of the aforementioned Riegl Laser Mirror Scanner. Alternatively, however, other detectors may be substituted.

The laser system **62** of the present embodiment further includes a beam directing device **124**, operable to direct the incident laser beam **112** to the environment **104** at a desired angle, which in this embodiment is vertical relative to a reference geoid. In this embodiment the beam directing device **124** is also locatable to direct the laser beam **114** scattered by the environment to the detector **122**.

More particularly, in this embodiment the beam directing device **124** includes a semitransparent mirror. The beam directing device receives the incident

laser beam **112**, or more particularly receives each successive **2** ns pulse, from the laser **120**, and reflects approximately **50**% of the photons in each such pulse toward the environment **104**. The remaining **50**% of the incident laser beam **112** passes through the beam directing device to a light stopper **126**, where it is effectively discarded.

The environment **104** scatters the received incident laser beam **112** to produce the laser beam **114** scattered by the environment, some of which is received at the beam directing device **124**. Approximately **50**% of this portion of the laser beam **114** scattered by the environment is transmitted through the beam directing device **124** and through a focusing lens **125** to the detector **122**, which then produces, as the first signals **56**, analog electrical signals whose voltage is proportional to the intensity of the received laser beam **114** scattered by the environment. The remaining **50**% is reflected back toward the laser **120**, and is absorbed by an absorber (not shown) interposed between the laser **120** and the beam directing device **124**. More particularly in this embodiment the absorber includes a disc-shaped absorptive plate having a central aperture therethrough allowing passage of the incident laser beam **112** from the laser **120** to the beam directing device **124**.

In the present embodiment, the laser system **62** also includes a motion mechanism shown generally at **128**, operable to adjust a physical orientation of the beam directing device **124** in response to an orientation signal, to direct the incident laser beam **112** to the environment **104** at the desired angle, which in this embodiment is vertically downward toward the environment.

In this regard, one of the many possible applications of the present embodiment is to obtain laser data representing the environment **104** directly beneath the aircraft **100** as it flies along a number of relatively straight flight lines. For this purpose, the aircraft **100** and a spot at which the incident laser

beam **112** strikes the environment **104** should ideally remain within a common vertical plane at all times during the aircraft's flight along the flight line. However, if the incident laser beam **112** always pointed in a fixed direction relative to the aircraft, then deviations from the desired aircraft motion would cause the incident laser beam **112** to point away from the vertical plane defined underneath the aircraft, and would therefore introduce measurement errors. More particularly, such deviations of aircraft motion may include "roll", (whereby the aircraft slightly rotates back and forth about a central axis pointing in the direction of its flight trajectory), "pitch" (whereby the aircraft rotates about a horizontal axis perpendicular to the direction of its flight trajectory, causing the nose to point upwards or downwards relative to a horizontal plane), and "yaw" (whereby the entire aircraft deviates from its desired straight line trajectory defining the flight line). However, in practice, it has been found that pitch does not tend to introduce significant measurement errors. Similarly, it has been found that yaw errors, which may be corrected using GPS data in any event, are also insignificant. However, correction for roll is desirable for many applications.

Accordingly, in the present embodiment the purpose of the motion mechanism **128** is to correct for "roll" of the aircraft **100** shown in Figure **3**, to ensure that the incident laser beam **112** is always pointing vertically downward at the environment **104**, rather than pointing toward a point laterally offset from a vertical plane defined beneath the aircraft as it flies in a straight flight line over the environment **104**. More particularly, in this embodiment the motion mechanism **128** provides roll stabilization of **±0.01** radians to the incident laser beam **112**. In the present embodiment the motion mechanism **128** accomplishes this by adjusting a physical orientation of the beam directing device **124** in response to an orientation signal, to direct the incident laser beam **112** to the environment **104**, at a desired orientation pointing vertically downwards.

In this embodiment the motion mechanism **128** includes an orientation monitoring device **130** operable to produce the orientation signal. More particularly, in this embodiment the orientation monitoring device **130** includes a single-axis fiber optic gyro, operable to produce signals in response to rotation of the aircraft **100** about a central axis pointing in the direction of flight of the aircraft. In this regard, suitable fiber-optic gyros are available from a number of vendors around the world, such as the E-Core **2000** FOG manufactured by KVH Industries, Inc. of Middletown, RI, USA, for example.

In this embodiment, the orientation monitoring device **130** produces an electrical orientation signal whose voltage is proportional to the angular rate of rotation of the aircraft **100** about its central axis, and whose polarity is determined by the direction of rotation. For example, if the aircraft is not rotating, a signal at a reference voltage is produced; rotation of the aircraft about its central axis (pointing in the flight direction) results in an electrical orientation signal having a voltage either exceeding the reference voltage in the case of positive rotation about the central axis or less than the reference voltage in the case of negative rotation, by a voltage difference proportional to the rate of rotation of the aircraft.

Alternatively, other types of fiber-optic gyros may be substituted. For example, rather than employing a "rate" gyro, a gyro including a built-in integrator, for producing an electrical orientation signal proportional to the amount (rather than the rate) of angular rotation may be substituted. Similarly, the orientation monitoring device need not include a fiber optic gyro, but may include any other device suitable for monitoring rotation about an axis, such as a mechanical gyro or an accelerometer system, for example.

In the present embodiment the motion mechanism **128** further includes a driver **132**, and a servo **134**. In this embodiment the driver **132** includes an

integrator (not shown), which receives the electrical orientation signal from the orientation monitoring device **130** representing the rate and direction of rotation of the aircraft **100**, and effectively integrates such rotational rate information to produce an integrated electrical orientation signal whose deviation from a reference voltage is proportional to an angular displacement of the aircraft **100** about its central axis relative to a horizontal position. In other words, the voltage of the integrated electrical orientation signal is proportional to the angle of the aircraft relative to the horizontal. For example, if the aircraft is horizontal, an integrated orientation signal at the reference voltage is produced; a positive rotation of the aircraft about its central axis (pointing in the flight direction) results in an integrated orientation signal having a positive voltage exceeding the reference voltage by an amount proportional to the angle of the aircraft relative to the horizontal position; and a negative rotation results in an integrated orientation signal less than the reference voltage by an amount proportional to the angle of the aircraft relative to the horizontal.

In this embodiment the driver **132** further includes a "reset integrators to zero" button (not shown), for error correction purposes. In this regard, it will be appreciated that integration of an angular rate R of rotation yields an angular displacement of $\varphi + k$, where k is a constant. Accordingly, the "reset integrators to zero" button may be actuated when the aircraft is in a stable horizontal orientation and is not rotating, to cause the integrator to produce the integrated orientation signal at precisely the reference voltage. However, it will be appreciated that over time, errors in the integrated angular displacement may accumulate, and may cause the integrator to produce the reference voltage when the aircraft is actually at a non-zero angular displacement relative to the horizontal. To prevent such errors from significantly accumulating, the "reset integrators to zero" button may be periodically actuated when the aircraft is horizontal. For example, in this

embodiment the integrators are reset to zero in this manner prior to commencement of each individual flight line flown by the aircraft **100**.

The servo **134** is attachable to the beam directing device **124**, and is operable to rotate the beam directing device **124** about an axis parallel to the central axis of the aircraft **100** (i.e., about an axis pointing in the flight direction of the aircraft). The servo also produces an electrical feedback signal whose deviation from a reference voltage varies in proportion to the angle at which the servo has rotated the beam directing device **124** relative to the aircraft **100**. In this embodiment the reference voltage of the servo **134** is the same as the reference voltage of the integrated orientation signal produced by the integrator of the driver **132**, however, the deviations from the reference voltage are in opposite directions compared to the corresponding deviations of the integrated orientation signal from its own reference voltage as described above.

In this embodiment, to ensure proper vertical alignment of the incident laser beam **112**, the driver **132** receives the orientation signal from the orientation monitoring device **130**, in response to which it produces the integrated orientation signal as described above. The driver **132** also receives the electrical feedback signal from the servo **134**. If the voltage and polarity of the integrated orientation signal do not precisely equal the voltage and polarity of the electrical feedback signal, the driver **132** supplies electrical power to the servo **134**, the polarity of such power being determined by the sign of the difference between the voltages of the feedback and integrated orientation signals, to cause the servo to rotate the beam directing device **124**. Such rotation in turn alters the voltage (and possibly polarity) of the electrical feedback signal produced by the servo, until the difference between the feedback and integrated orientation signals is reduced to zero, at which point no further power is supplied by the driver to the servo. For example, if the

aircraft **100** is initially flying in a perfectly horizontal plane, with the beam directing device also horizontal, the orientation and electrical feedback signals are both at the reference voltage, and the difference is zero. If the aircraft then "rolls", or more particularly, positively rotates by an angle φ about its central axis pointing in its flight direction, the integrator of the driver **132** receives orientation signals from the orientation monitoring device **130**, in response to which it produces an integrated electrical orientation signal exceeding the reference voltage in proportion to the angle φ by which the aircraft has rolled. At the instant of such a roll, before the servo reacts, the feedback signal produced by the servo is still at the reference voltage. The driver **132** supplies power to the servo **134** whose polarity is determined by the sign of the difference between the feedback and integrated orientation signals, which in this case is negative, causing the servo to rotate the beam directing device **124** in a negative direction. Such negative rotation also causes the servo **134** to produce a positive electrical feedback signal whose voltage exceeds the reference voltage in proportion to the amount by which the servo has rotated the beam directing device relative to the aircraft. Such negative rotation continues until the servo has rotated the beam directing device in a negative direction by the same angle as the aircraft has rotated in a positive direction, at which point the feedback and integrated orientation signals are equal and the driver ceases supplying power to the servo. It will be appreciated that at this point, the beam directing device **124** will once again be directing the incident laser beam **112** vertically downwards, having effectively corrected for any such roll of the aircraft **100**.

Alternatively, other suitable motion mechanisms may be substituted for the motion mechanism **128**. In this regard, for many applications it is desirable to be able to provide roll correction accurate to $\pm$ **0.01** radians. Similarly, if desired, correction for pitch and/or yaw may be substituted or added.

In this embodiment, further manual fine adjustment of the vertical orientation of the beam may be performed if desired. For example, the servo **134** may include a manual adjustment control (not shown) which allows the zero-point of the servo (i.e., the angle at which the servo produces the electrical feedback signal at the reference voltage) to be manually adjusted. The aircraft **100** may then fly over calm (flat) water, with the aircraft flying in a level horizontal plane, and the orientation of the servo, and hence of the beam directing device **124**, may be finely manually adjusted to provide a maximum return signal level of the laser beam **114** scattered by the environment.

If desired, the laser system **62** may include additional optical components (not shown). In this embodiment, the laser system **62** is installed in the aircraft **100**, with the laser **120**, the beam directing device **124**, the servo **134**, the light stopper **126** and the detector **122** installed in a baggage pod area of the aircraft **100**. The orientation monitoring device **130**, driver **132**, and related electronic components, including the central processing system **60** shown in Figure **2**, are installed within a cabin area of the aircraft. In the present embodiment, suitable windows (not shown) are installed to prevent debris from entering the baggage pod, and to allow the laser beam to exit without attenuation.

Also in this embodiment, the laser system **62** may be calibrated prior to use if desired. For example, the incident laser beam **112** may be directed at a nearby low-reflectivity target (not shown) on the ground prior to takeoff of the aircraft **100**, and neutral density filters (not shown) may be interposed between the target and the detector **122** to simulate attenuation that would be experienced at flight altitudes. The resulting data produced by the central processing system **60** representing the distance to the target may be compared to the known distance to the target, and calibration may then be performed if required.

Radar Transmission System

Referring to Figures **2**, **3**, **4** and **6**, the radar transmission system is shown generally at **66** in Figure **6**. In this embodiment, the radar transmission system **66** includes the transmission antenna system **108**, which in this embodiment includes first and second transmission antennae **140** and **142** respectively. In this embodiment, each of the transmission antennae is tuned to a bandwidth (**3** dB) of **180** - **420** MHz, has an efficiency in excess of **25**%.

In this embodiment, the radar system **64**, or more particularly the radar transmission system **66**, is configured to direct to the environment **104**, as the incident radar beam **102**, an ultra-wide band (UWB) radar beam. The radar transmission system directs the UWB incident radar beam to the environment **104**, to produce the radar beam **106** scattered by the environment. To achieve this, in the present embodiment the radar transmission system **66** includes an ultra-wide band (UWB) transmitter **144**, in communication with the transmission antenna system **108**.

In the present embodiment the UWB transmitter **144** receives a triggering signal from the central processing system **60** shown in Figure **2**, at a desired rate at which UWB radar pulses are to be produced. In this embodiment, it is desirable to produce radar pulses at a rate of at least one per meter of travel of the aircraft **100**, which in this embodiment typically flies at a groundspeed of less than **270** km/h or **75** m/s. Accordingly, in this embodiment the desired pulse repetition rate is **75** radar pulses per second.

In response to each triggering signal received from the central processing system **60**, which in this embodiment is received once every **1/75**th of a second, the UWB transmitter **144** generates and transmits an electrical impulse signal to the transmission antenna system **108**. More particularly, in this embodiment the impulse signal is a unipolar impulse signal having a

duration of approximately **3.3** ns, a voltage of approximately **1** kV, a rise time (**10** - **90**%) of less than **1** ns and a pulse width (**3** dB points) of **1.7**$\pm$**0.3** ns. The UWB transmitter in the present embodiment produces such impulse signals to have a short-term phase jitter of less than **50** ps over a **10** s period and a long-term jitter of less than **250** ps over a **30** minute period. In this embodiment the UWB transmitter **144** includes a transmitter manufactured by the Ioffe Research Institute of St. Petersburg, Russia operable to produce a **10** kV impulse signal, and further includes an attenuator (not shown) to produce the desired **1** kV impulse signal. Alternatively, other types of impulse signals and/or other types of UWB transmitters may be substituted, such as a model AVG-3B-C transmitter manufactured by Avtech Electrosystems Ltd. of Ottawa, Canada, for example. It is preferable, however, that the UWB transmitter be capable of accurately producing unipolar impulse signals as described above, and be capable of accurately operating at ambient temperatures of at least **27**°C (**80**°F).

In response to the impulse signal, the transmission antenna system produces and tune a **3.3** ns electromagnetic radar pulse over an ultra-wide band frequency range between **200** MHz and **400** MHz. More particularly, in this embodiment the transmission antenna system **108** produces the radar pulse at a power ranging from approximately **9** W at **200** MHz to **1.5** W at **400** MHz.

In the present embodiment the transmission antenna system **108** is configured to produce the radar pulse to extend over a spot size of the environment **104** of approximately **25** m per **1000** ft (**300** m) AGL, or in other words, to have a beam width of approximately **5**°.

It will be appreciated that the wavelength of the UWB radar pulse in the present embodiment ranges from **1.5** m to **0.75** m, with the center frequency of **300** MHz having a wavelength of **1** m. Therefore, by order of magnitude,

the radar transmission system **66** of the radar system **64** is configured to transmit, as the incident radar beam **102**, a radar beam having a wavelength of at least on the order of one meter. Thus, in this embodiment the wavelength of the incident radar beam **102** is between **0.7** and **2** m. Alternatively, however, other wavelengths may be substituted, although it is noted that wavelengths longer than **2** m tend to result in poorer resolution, while wavelengths shorter than **0.7** m tend to result in poorer ground penetration.

More generally, other radar transmission systems may be substituted.

Radar Reception System

Referring to Figures **2**, **3**, **4** and **7**, the radar reception system of the radar system **64** is shown generally at **68** in Figure **7**.

In the present embodiment, the radar reception system **64** is installed in the aircraft **100** shown in Figure **3**, and may therefore be referred to as an airborne radar reception system or receiver. As the radar transmission system **66** in the present embodiment transmits, as the incident radar beam **102**, a radar beam having a wavelength of at least on the order of one meter, the radar reception system **68** is therefore configured to receive, as the radar beam **106** scattered by the environment **104**, a radar beam having a wavelength of at least on the order of one meter. More particularly, in this embodiment the radar reception system is configured to receive, as the radar beam scattered by the environment, a radar beam having a wavelength between **0.7** and **2** meters, or more particularly still, between **0.75** and **1.5** meters.

Generally, in the present embodiment, the radar reception system **68** is operable to produce signals, or more particularly the second signals **58**, in response to the radar beam **106** scattered by the environment **104**.

In this embodiment, the radar reception system **68** includes the reception antenna system **110**, and further includes a receiver shown generally at **150**.

Referring to Figures **2** and **7**, in the present embodiment, the reception antenna system **110** includes first, second, third, fourth, fifth and sixth antennae **152**, **154**, **156**, **158**, **160** and **162** respectively. In this present embodiment, the first, second and third antennae **152**, **154** and **156** are mountable on a port wing **164** of the aircraft **100** shown in Figure **2**, while the fourth, fifth and sixth antennae are mountable on a starboard wing **166**, symmetrically opposite the first, second and third antennae. More particularly, in the present embodiment the antennae **152** through **162** are mounted orthogonally with respect to a forward direction of flight of the aircraft **100**, so that nulls in the resulting antenna pattern are projected to the sides of the flight path.

In this embodiment the antennae **152** through **162** are constructed in three stages. Stand-off pieces, such as that shown at **168** in Figure **2** for example, are fabricated from aluminum strut material, and are cut and welded so as to mount the antennae, such as that shown at **170**, a distance of one-quarter wave from each of the wings **164** or **166**. In this embodiment, the center frequency of the UWB pulse has a wavelength of **1** m, and therefore, each stand-off piece is constructed to mount each respective antenna **0.25** m below its respective wing. Next, an antenna electrical section or active element is constructed as a broadband fat dipole with resistive loading, and is laid upon G-**100.25**" board. Finally, the active element is encased in fiberglass to form the antenna, such as the antenna **170** for example, which is then attached to

the stand-off piece. Each antenna may then be tested for electrical performance, and for mechanical load carrying capacity in accordance with FAA directives. In this embodiment, each of the resulting antennae is tuned to a bandwidth (**3** dB) of **180** - **420** MHz, and has an efficiency in excess of **25**%.

In the present embodiment the radar system **64**, or more particularly the reception antenna system **110**, further includes a delay device **172**, operable to delay signals produced by at least some of a plurality of antennae (or more particularly, the antennae **152** through **162**) of the reception antenna system **110**.

In this regard, it will be appreciated that for the purpose of measuring the environment **104** at a point directly beneath the aircraft **100**, portions of a radar pulse scattered or reflected by such a point will arrive at the antennae closest to a fuselage **174** of the aircraft **100** slightly before portions of the same pulse scattered by the same point arrive at the antennae mounted further from the fuselage **174**, which are geographically further away from the point of the environment **104**. This effect diminishes as altitude of the aircraft **100** increases, as the angle formed by the antenna most distal from the fuselage, the point of the environment **104**, and the antenna most proximal to the fuselage, decreases with increasing altitude.

Accordingly, in order to improve the synchronization of the electrical signals produced by the antennae **152** through **162** in response to a given radar pulse scattered by the environment, it is desirable to introduce a delay into the electrical signals produced by each of the antennae, in inverse proportion to its distance from the fuselage and the altitude of the aircraft. Although the actual amounts of such delays will vary from application to application depending on altitude and the spacing and configuration of the antennae, a

simplified model may be demonstrated for illustrative purposes. For example, assuming that the port and starboard wings **164** and **166** lie in a horizontal plane and extend perpendicular to a central axis (not shown) of the fuselage **174**, and assuming the antennae are mounted in the order shown in Figure **7**, i.e., with the antenna **152** at the outer edge of the port wing **164** a distance S_{152} from the central axis of the fuselage, antenna **154** mid-way along the port wing a distance S_{154} from the fuselage, and antenna **156** at an inner portion of the port wing a distance S_{156} of the fuselage, then geometrically, the relative delay time that is desirable for antenna **156** may be shown to be:

$$t_{156} = \frac{\sqrt{h^2 + S_{152}{}^2} - \sqrt{h^2 + S_{156}{}^2}}{c} \qquad (1)$$

wherein

t_{156} = the desired delay time for antenna **156**, in seconds;

h = the height of the horizontal plane in which the antennae **152** and **156** lie when the aircraft **100** is flying level, above the point of interest of the environment, in meters (for present purposes, this height may be assumed to equal the altitude of the aircraft **100**);

S_{152} = the horizontal distance between the antenna **152** and the central axis of the fuselage **174**, in meters;

S_{156} = the horizontal distance between the antenna **156** and the central axis of the fuselage **174**, in meters; and

c = the speed of light, in meters per second.

Similarly, the desired delay for the antenna **154** is:

$$t_{154} = \frac{\sqrt{h^2 + S_{152}{}^2} - \sqrt{h^2 + S_{154}{}^2}}{c} \tag{2}$$

and no delay is required for antenna **156**.

Similarly, assuming the antennae **158**, **160** and **162** are mounted on the starboard wing **166** symmetrically opposite the antennae **156**, **154** and **152**, then the delays for antennae **158** and **160** are the same as those for antennae **156** and **154** respectively, and antenna **162** is not delayed.

In order to effect such delays, in the present embodiment the delay device **172** includes a plurality of delay cables. More particularly, in this embodiment the delay cables include first and second delay cables **175** and **176** in communication with the antennae **156** and **158** respectively, for providing a delay t_{156} as described above. In this regard, each of the delay cables **175** and **176** includes a **50**-ohm impedance cable, in which electrical signals propagate at approximately a speed of approximately (**2/3**)c. Thus, the length of the delay cables **175** and **176** in the present embodiment is l_{174} = (**2/3**)ct_{156}. Similarly, the delay cables include third and fourth delay cables **178** and **180**, in communication with the antennae **154** and **160** respectively, each of length (**2/3**)ct_{154}. Aside from such delay cables, each of the antennae **152** through **162** is in communication with an output port **182** of the delay device **172** along an equal length of cable, so that signals produced by each of the antennae **152** through **162** arrive at the output port **182** in an equal amount of time, except for the delays introduced by the delay cables **175** through **180**.

In the present embodiment, the lengths of the delay cables **175** through **180** are calculated on the assumption of an arbitrary typical height h = **1000** ft (**300** m) above the hypothetical point in the environment. In this regard, in the present embodiment the delay device **172** is intended to provide relatively unfocussed delay correction, and is therefore suitable for altitudes ranging

from **150** m to **450** m. However, in addition to the delay device **172**, the radar reception system **68** includes further delay devices (not shown), with delay cable lengths configured for different flight altitudes. The delay device **172** in the present embodiment is configured as an easily detachable delay box, which is easily replaceable during flight with an alternative delay box with delay cables shortened or lengthened to correspond to a higher or lower flight altitude respectively.

Referring to Figures **2**, **3**, **4** and **7**, in this embodiment, the radar reception system **68** further includes a blanker **190** operable to blank transmitter cross-talk signals while directing the incident radar beam **102** to the environment **104**. In this regard, due to the close physical proximity of the reception antenna system **110** to the transmission antenna system **108**, a portion of the incident radar beam **102** itself (as opposed to its scattered return from the environment) tends to be inadvertently received at the reception antenna system **110**. In response to this directly-received portion of the incident radar beam **102**, the reception antenna system **110** produces electrical signals (referred to herein as transmitter cross-talk signals) vastly more powerful than the signals it produces in response to the scattered return of the radar beam from the environment. However, as the receiver **150** is configured to receive much lower-power electrical signals produced in response to the radar beam **106** that has been scattered by the environment, the signals produced in response to the directly-received portion of the incident radar beam **102** may tend to overload or damage various components of the receiver.

To prevent such damage, in the present embodiment the blanker **190** is configured to block all electrical signals produced at the output port **182** of the reception antenna system **110**, thereby preventing such transmitter cross-talk signals from reaching the receiver **150**, during successive time intervals in which each successive pulse of the incident radar beam **102** pulse is

transmitted by the radar transmission system **66**. To achieve this, in the present embodiment the blanker **190** includes an input port **192** for receiving the second signals **58** from the reception antenna system **110**, a control input port **194** for receiving control signals from the central processing system **60**, and an output port **196** for forwarding the second signals **58** to the receiver **150**. In this embodiment, as discussed in greater detail below, the blanker **190** receives control signals at the control input port **194** from the central processing system **60**, causing it to commence blanking the transmitter cross-talk signals received from the reception antenna system **110** at a first time preceding transmission of each successive pulse of the incident radar beam **102**, and to cease blanking such signals at a second time following the transmission of each such pulse. As discussed in greater detail below, the interval defined between the first and second times is selected so as to be long enough to blank any transmitter cross-talk signals produced in response to the incident radar beam **102**, but not to blank any signals produced in response to the radar beam **106** scattered by the environment **104**.

Referring to Figures **2**, **3** and **7**, in this embodiment the second signals **58** produced by the reception antenna system **110** in response to the radar beam **106** scattered by the environment **104**, are then received at the receiver **150** shown in Figure **7** (except during blanking intervals of the blanker **190**).

Generally, the receiver **150** serves to adjust the amplitude and frequency of the second signals **58**, for the purpose of subsequent digitization. With respect to signal amplitude, the purpose of the receiver **150** in the present embodiment is to supply the second signals **58** to a digitizer (discussed below) such that a background noise level of the second signals has sufficient amplitude to toggle a least significant bit of the digitizer, and a maximum or saturation level of the second signals has just enough amplitude to toggle a most significant bit of the digitizer.

With respect to frequency, the receiver **150** serves to down-shift the frequency of the second signals **58** to less than half of the sampling rate of the digitizer, to permit digitization without Nyquist aliasing that would otherwise result. In this regard, in the present embodiment the receiver **150** receives the second signals **58**, frequency-shifts the second signals, and outputs the second signals as in-phase frequency-shifted signals and in-quadrature frequency-shifted signals, both of which range from baseband to half the original bandwidth of the second signals (**0** - **100** MHz). The receiver **150** preferably has an overall noise figure of **3** dB, a dynamic range of **48** dB, a bandwidth (**3** dB) in excess of **200** MHz, and a phase linearity of **30** degrees.

In this embodiment, to achieve the foregoing purposes, the second signals **58** are first received at a limiter **200** of the receiver **150**, which in this embodiment is a -**1**dB limiter. The limiter **200** serves a purpose similar to that of the blanker **190**, to prevent inadvertent overload of various components of the receiver **150** in the event that the signal levels of the second signals **58** received from the reception antenna system **110** dramatically exceed expected values. In this embodiment the limiter **200** effectively clips or limits the signal excursion of the second signals, limiting their signal level to +**13** dBm, or about $\pm$ **1** V.

In this embodiment, signals output from the limiter **200** are then received at a an amplifier **202**, which in this embodiment is a low-noise +**15**dB amplifier.

Referring to Figures **2** and **7**, in the present embodiment, following such low-noise amplification, the amplified second signals **58** output from the amplifier **202** are received at an attenuator **204**, which in this embodiment is operable to adjustably attenuate the second signals. More particularly, in this embodiment the attenuator **204** includes an input port **206**, a control input port **208** and an output port **210**. The attenuator **204** is in communication with a

radio frequency (RF) gain control device **212**, which includes a control input port **214** and a control output port **216**. The RF gain control device **212** is in further communication with a manual gain control device **218**, which in this embodiment is a five-position manual switch. In response to user actuation of the manual gain control device **218**, to place the switch in one of five positions shown in Figure **7**, the manual gain control device produces a respective one of five corresponding distinct control signals, which is received at the control input port **214** of the RF gain control device **212**.

The manual gain control device further includes a gain monitor connection **220**, which is in communication with the central processing system **60** shown in Figure **2**, to provide the central processing system with an indication of the gain or attenuation level at any given time.

In this embodiment, the five positions of the manual gain control device **218** correspond to various flight altitudes. For example, in this embodiment a first switch position corresponds to a flight altitude of **1000** ft or higher, for which minimal or no attenuation is desired, and conversely, a fifth switch position corresponds to a flight altitude of **50** ft, for which a maximum attenuation is desired, due to the high intensity of the radar beam **106** scattered by the environment as detected from such a low altitude, and the remaining switch positions correspond to intervening altitudes for which respective intermediate attenuation levels are desired. Alternatively, if desired, the central processing system may be placed in communication with an on-board navigation computer (not shown) of the aircraft **100**, and may automatically adjust the attenuation of the second signals **58** in response to altitude of the aircraft.

In response to the control signal received at its control input port **214**, the RF gain control device **212** in the present embodiment produces a control signal

at its output port **216** at one of five discrete current levels corresponding to the particular control signal produced by the manual gain control device **218**.

In this embodiment the control signal produced at the control output port **216** of the RF gain control device **212** is received at the control input port **208** of the attenuator **204**. In the present embodiment, the attenuator **204** attenuates the second signals **58** received at its input port **206** by an amount corresponding to the current of the control signal received at its control input port **208**, and supplies the attenuated second signals **58** at the output port **210** of the attenuator. More particularly, in this embodiment the attenuated second signals **58** produced at the output port **210** are adjustably attenuated between **0**dB and **-30**dB relative to their strength upon arrival at the input port **206**. More particularly still, in this embodiment the five attenuation levels corresponding to the five positions of the manual gain control device **218** are **0** dB, **6** dB, **12** dB, **20** dB and **30** dB respectively.

In this embodiment, the attenuated second signals **58** produced at the output port **210** of the attenuator **204** are then received at an amplifier **222**. In this embodiment, the amplifier **222** is a **+31**dB voltage amplifier.

In the present embodiment the amplified second signals **58** produced by the amplifier **222** are then supplied to a combiner **224**, which is in communication with a calibration signal generator **226**. More particularly, in this embodiment the calibration signal generator **226** produces a calibration signal at a frequency within the range of the UWB pulse produced by the radar transmission system **66**. More particularly still, in this embodiment the calibration signal generator **226** produces, as the calibration signal, a sine wave signal at a frequency of **320**MHz, at a level of **0**dBm.

The combiner **224** receives the calibration signal, attenuates it by **-66** dB, and inserts the attenuated **-66** dBm calibration signal into the second signals **58**.

As discussed in greater detail below, the calibration signal may be used to provide phase and amplitude tracking between I and Q channels and to monitor channel balance and digitizing errors.

Referring to Figures **2**, **3**, **4** and **7**, in this embodiment, the second signals **58**, now including the calibration signal, are then supplied to a frequency-shifter, shown generally at **227** in Figure **7**. In the present embodiment the frequency-shifter **227** is operable to produce the second signals **58** by producing frequency-shifted signals in response to the radar beam **106** scattered by the environment. More particularly, in this embodiment the frequency-shifted signals correspond to sum and difference frequencies resulting from mixing initial electrical signals produced in response to the radar beam **106** with a mixing frequency.

In this regard, in this embodiment the radar system **64**, or more particularly the radar reception system **68**, is configured to produce the second signals **58** by first producing initial electrical signals at frequencies of the radar beam **106** scattered by the environment **104**, in response thereto. More particularly, in this embodiment such frequencies include frequencies between **200** and **400** MHz, and the initial electrical signals, such as those output from the combiner **224** for example, are produced at these frequencies. It will be appreciated that in order to accurately digitally sample **400** MHz signals to avoid aliasing, it would be necessary to sample at a rate greater than the Nyquist frequency of **800** MHz for such signals. However, it has been found that many commercially-available digitizers tend to be unreliable at sampling rates significantly greater than **500** MHz. For example, some such digitizers interleave two separate **500** MHz sampling frequencies, which tend to drift apart over time. In order to address this difficulty, the frequency-shifter **227** serves to down-shift the frequencies of the second signals **58**, to frequencies below **250**MHz (or more particularly, baseband frequencies below **100**MHz),

to allow the second signals **58** to be reliably sampled with a commercially-available **500** MHz digitizer.

To achieve this, in the present embodiment the frequency-shifter **227** includes a mixer operable to produce the frequency-shifted signals in response to the initial electrical signals and a mixing frequency signal. More particularly, in this embodiment the frequency-shifter **227** includes a power splitter **228**, a first mixer **236**, a second mixer **244**, a phase-shifter **252**, an oscillator **260**, and amplifiers **266** and **268**.

More particularly still, in this embodiment the second signals **58** output from the combiner **224** are first received at an input port **230** of the power splitter **228**. The power splitter **228** simultaneously supplies the incoming second signals **58** to a first output port **232** and a second output port **234**, effectively dividing the second signals into a first channel and a second channel, each identical to the incoming second signals **58** except for their respective energy levels. In this regard, the power splitter **228** equally divides the energy of the second signals **58** among the two channels, and therefore, each channel of the second signals **58** produced at the first and second output ports has a signal strength of -**3**dB relative to the strength of the second signals **58** received at the input port **230**. In this embodiment the two channels of the second signals **58** are supplied at identical phase to the output ports **232** and **234**, which supply the first and second channels to the first and second mixers **236** and **244** respectively.

Generally, in this embodiment the mixers **236** and **244** receive the first and second channels of the second signals **58**, and also receive mixing frequency signals, in response to which the mixers frequency-shift the second signals **58**.

In order to produce the mixing frequency signals, in this embodiment the receiver **150** includes the oscillator **260**, which is configured to produce a mixing frequency signal at the center frequency of the ultra-wide band of the radar beam **106** scattered by the environment, which in this embodiment is **300** MHz. The oscillator **260** receives a control signal from the central processing system **60** at a control signal input port **262**, which in this embodiment includes a **10** MHz clock signal. In response to the received control signal, the oscillator **260** produces a phase coherent **300** MHz mixing frequency signal, at a signal level of -**4** dBm, at an output port **264** of the oscillator.

The **300** MHz mixing frequency signal is then received and amplified by the amplifiers **266** and **268**, which in this embodiment include a +**6** dB amplifier and a +**8** dB amplifier respectively. Alternatively, one or more other amplification devices may be substituted.

The amplified mixing frequency signal is then supplied to an input port **254** of the phase-shifter **252**. In this embodiment, the phase-shifter **252** includes a hybrid coupler which simultaneously supplies the received amplified mixing frequency signal to first and second output ports **256** and **258**, effectively defining two mixing frequency channels. In this regard, the phase-shifter **252** divides the energy of the incoming amplified mixing frequency signal equally among the two channels, so that the mixing frequency signal produced at each of the output ports **256** and **258** has a signal level of -**3** dB relative to the signal level of the mixing frequency signal received at the input port **254** (more particularly, each of the two signals is produced at +**7** dBm). However, in this embodiment the phase-shifter **252** introduces a **90°** or one-quarter cycle phase delay in the mixing frequency signal produced at the second output port **258** relative to that produced at the first output port **256** of the phase-

shifter. The mixing frequency signals produced at the output ports **256** and **258** are then supplied to the mixers **236** and **244**.

In this embodiment, the frequency-shifter **227** is operable to produce, as the frequency-shifted signals, in-phase frequency-shifted signals and in-quadrature frequency-shifted signals. In this regard, in the present embodiment, as discussed below, the center frequency of the second signals **58** is effectively down-shifted from **300** MHz to baseband (**0** MHz), so that the frequency-shifted second signals **58** include both positive (real) frequencies between **0** and **100** MHz, as well as negative frequencies between -**100** MHz and baseband. Accordingly, in order to fully represent the second signals **58**, including such negative frequencies, both an in-phase component and an in-quadrature component (each from **0** to +**100** MHz) are required in order to express the second signals as complex vectors or phasors having respective real and imaginary components.

To produce the in-phase frequency-shifted signals, in the present embodiment the mixer **236** includes an input port **238**, a mixing signal input port **240**, and an output port **242**. At the input port **238**, the mixer **236** receives the first channel of the second signals **58** supplied from the output port **232** of the power splitter **228**. In addition, at the mixing signal input port **240**, the mixer **236** receives the mixing frequency signal from the first output port **256** of the phase-shifter **252**. In response to the first channel of the second signals and the mixing frequency signal, the mixer **236** frequency-shifts the first channel of the second signals **58** to produce frequency-shifted signals, which are supplied at the output port **242**. More particularly, it will be appreciated that the mixer **236** will produce a number of difference and sum frequency range, including a first difference frequency range $f_{UWB} - f_M$, a first sum frequency range $f_{UWB} + f_M$, and so on, where f_{UWB} is the frequency range of the second signals **58** upon arrival at the input port **238** (in this embodiment, **300** $\pm$ **100**

MHz), and f_M is the mixing frequency (in this embodiment **300** MHz). Thus, in this embodiment the first difference frequency range is **0** $\pm$ **100** MHz, and the first sum frequency range is **600** $\pm$ **100** MHz.

Similarly, to produce the in-quadrature frequency-shifted signals, in this embodiment the mixer **244** includes an input port **246**, a mixing signal input port **248**, and an output port **250**. At the input port **246**, the mixer **236** receives the second channel of the second signals **58** supplied from the output port **234** of the power splitter **228**. In addition, at the mixing signal input port **248**, the mixer **244** receives the mixing frequency signal from the second output port **258** of the phase-shifter **252**, which in this embodiment is phase-delayed **90°** relative to the mixing frequency signal received at the mixer **236**. In response to the second channel of the second signals and the phase-delayed mixing frequency signal, the mixer **244** frequency-shifts the second channel of the second signals **58** to produce frequency-shifted signals, which are supplied at the output port **250**. More particularly, in this embodiment the mixer **244** produces a number of difference and sum frequency ranges identical to the frequency ranges produced by the mixer **236**, including the first difference frequency range of **0** $\pm$ **100** MHz. However, in this embodiment the frequency-shifted signals produced by the mixer **244** at such frequencies are phase-delayed by **90°** relative to the corresponding signals produced at the mixer **236**, due to the phase-delay of the incoming mixing frequency signal received at the mixer **244**.

Thus, as a result of the frequency-shifter **227**, the second signals **58** are effectively divided into an in-phase frequency-shifted channel produced at the output port **242** of the mixer **236** (hereinafter referred to as the "I" channel), and an in-quadrature frequency-shifted channel produced at the output port **250** of the mixer **244** (hereinafter referred to as the "Q" channel).

The I-channel signals are then received at a filter **270**, which in this embodiment includes a **100** MHz low-pass filter. The filter **270** serves to remove all "sum" signals produced by the mixer **236**, such as the first sum frequency range of **600** $\pm$ **100** MHz for example, and passes only the first difference frequency range of **0** $\pm$ **100** MHz, or more particularly, the **0** - **100** MHz real component of such frequencies.

In this embodiment, the **0** - **100** MHz I-channel signals are then received at a limiter **272**, followed by successive amplifiers **274** and **276**. In this regard, it will be appreciated that many typical amplifiers have poor responses, including significant drift and phase distortion, at frequencies below **10** MHz. Accordingly, in order to provide adequate amplification of the frequency-shifted **0** - **100** MHz I-channel signals, the amplifiers **274** and **276** include respective baseband amplifiers, sometimes referred to as video amplifiers, capable of amplifying the I-channel signals with minimal drift and phase distortion across the entire range from DC (O MHz) to **100** MHz. More particularly, in this embodiment the amplifier **274** includes a **+31** dB baseband amplifier, and the amplifier **276** includes a **+15** dB baseband amplifier.

As such baseband amplifiers are typically expensive, the limiter **272** serves to provide added protection for the baseband amplifiers against overloads, which may arise due to saturation of upstream amplifiers, coupling between cables, poor shielding, etc. In the present embodiment the limiter **272** is a hard limiter operable to clip or limit the power of incoming I-channel signals to prevent overload of the baseband amplifiers **274** and **276**.

Amplified I-channel signals from the baseband amplifier **276** are then communicated, via an I-channel exit port **278** of the receiver **150**, to the central processing system **60** shown in Figure **2**.

Similarly, in this embodiment, Q-channel signals from the mixer **244** are passed through a filter **280**, a limiter **282**, and baseband amplifiers **284** and **286**, which are identical to the corresponding I-channel components **270**, **272**, **274**, **276**. Q-channel signals are processed by such components in the same manner as described above in connection with the I-channel signals, and are then communicated, via a Q-channel exit port **288**, to the central processing system **60**.

Thus, following processing by the receiver **150** as described above, the second signals **58** produced in response to the radar beam **106** scattered by the environment **104** are transmitted to the central processing system **60** in the form of **0** - **100** MHz I-channel signals, and **0** - **100** MHz Q-channel signals in quadrature with the I-channel signals.

If desired, prior to use of the radar reception system **68** to measure the environment **104**, the calibration signal inserted by the calibration signal generator **226** and combiner **224** may be used to balance the I-channel and Q-channel signals. For example, a network analyzer may be connected to the I-channel and Q-channel exit ports **278** and **288**. The calibration signal, which in this embodiment was generated as a **320** MHz sine-wave and down-shifted to **20** MHz by the frequency-shifter **227**, may be decomposed from the I-channel and Q-channel signals using any suitable method (such as a fast Fourier transform, for example). If the amplitudes of the decomposed calibration signals of the I-channel and Q-channel signals do not match, or if they are not precisely **90°** out of phase, then various components of the receiver **150**, such as the amplifiers or phase-shifter for example, may be adjusted until the I-channel and Q-channel calibration signals are balanced, with equal amplitude and the desired **90°** phase difference. In this embodiment, such calibration is performed once per flight mission. However, if in a given embodiment the receiver **150** is particularly unstable, it may be

desirable to perform such calibration more often, such as once per flight line for example. Alternatively, if desired, rather than performing such calibration in response to the analog signals produced at the I-channel and Q-channel exit ports **278** and **288**, such calibration may be performed in response to corresponding digital signals produced by the central processing system, as described below.

Central Processing System

Referring to Figures **2**, **4** and **8** (comprising Figures **8a** and **8b**), the central processing system (CPS) is shown generally at **60** in Figure **8**. In this embodiment, the CPS **60** includes the processor circuit **54**, which in this embodiment includes a microprocessor **300**, or more particularly, a **1.3** GHz Pentium-**4** microprocessor. More generally, however, in this specification including the claims, the term "processor circuit" is intended to broadly encompass any type of device capable of processing signals for the purposes described herein, including (without limitation) other types of microprocessors, microcontrollers, other integrated circuits, other types of circuits or combinations of circuits, logic gates or gate arrays, or programmable devices of any sort, either alone or in combination with other such devices located at the same location or remotely from each other, for example.

The processor circuit **54** is in communication with the memory device **52**, which in this embodiment includes a hard disk drive. Alternatively, however, any other suitable memory device, such as compact discs (CDs), other types of magnetic disks or diskettes, optical storage devices, magnetic tapes, random access memories (RAMs), programmable read-only memories such as EPROMs, EEPROMs or FLASH memories, for example, or any other type of memory device, either at the location of the processor circuit or located remotely therefrom, may be substituted if desired.

In this embodiment the memory device **52** is used to store data shown generally at **302** representing the first and second signals **56** and **58**, for use in producing a representation of the environment **104**. In the present embodiment the memory device **52** also acts as a computer readable medium providing instructions, including a plurality of routines shown generally at **304**, for directing a processor circuit to perform the functions associated with the various routines described herein. However, the hard disk drive is merely one example of a suitable memory device for either of the above purposes. Alternatively, such routines may be provided as software stored on a different medium such as those described earlier herein, for example, or available from a communications medium such as the Internet, for example.

Alternatively, such routines may be provided as signals comprising code segments for directing a processor circuit to perform similar or equivalent functions to those described herein. In the present embodiment such signals may be produced on a signal line **306** via which the processor circuit **54** and memory device **52** are in communication, however, alternatively, any other suitable way of producing such signals may be substituted.

More particularly, in the present embodiment the routines **304** include a measurement routine **308**, which in turn includes a timing thread **310**.

In this embodiment the routines **304** also include an analysis routine **320**, which in turn includes a migration subroutine **322** and a separation subroutine **324**. In this regard, in the present embodiment, the processor circuit **54** also acts as a representation processing circuit, configured to produce the representation of the environment **104** in response to the data **302** representing the first and second signals **56** and **58**. Alternatively, however, for many applications it will be unnecessary to perform such analysis with the same processor circuit **54** which executes the measurement routine **308**, as

the analysis may typically be performed on the ground, after the aircraft **100** has landed following a flight during which the data **302** representing the first and second signals **56** and **58** has been stored. Alternatively, therefore, the representation processing circuit may include a processor circuit other than the processor circuit **54**, such as a processor circuit of a land-based desktop computer, for example.

In this embodiment the analysis routine **320** further includes a contouring routine **325**, which in this embodiment includes ANUDEM software, available from the Centre for Resource and Environmental Studies of the Australian National University, in Canberra, Australia. Alternatively, other contouring routines may be substituted.

In the present embodiment, the processor circuit **54** is in further communication with a second memory device **329**, which in this embodiment includes a random access memory (RAM) **330**.

Referring to Figures **2**, **7**, **8a** and **8b**, in this embodiment, the measurement routine **308** in the memory device **52** directs the processor circuit **54** to define a plurality of registers or stores in the RAM **330**, including a data store **332**, for storing at least one data structure such as that shown generally at **334**, including a laser field **362** for storing data representing the first signals **56** and a radar beam field **360** for storing data representing the second signals **58**.

In this embodiment, the data structure **334** further includes a measurement context field shown generally at **336** for storing measurement context information. In this embodiment the measurement context field **336** includes a GPS sub-field **338** for storing data received from the GPS device **80**, a gain monitoring sub-field **340** for storing data representing the position of the manual gain control device **218** of the radar reception system **68**, and a manual data sub-field **342** for storing user-inputted information. More

particularly, in this embodiment the manual data sub-field **342** includes a flight line sub-field **344** for storing a number representing a present flight line or path of the aircraft **100**, a mission sub-field **346** for storing an identification of a present flight mission (for example, a single flight mission typically comprises a plurality of flight lines), a comments sub-field **348** for storing other user-inputted information which may be relevant to the interpretation of the data **302** produced and stored during the course of the flight, and a time sub-field **350** for storing a value representing a time at which the data structure **334** was stored.

In addition, in this embodiment the data structure **334** includes the radar beam field shown generally at **360**, for storing data representing the second signals **58** produced in response to a radar beam scattered (more particularly, the radar beam **106**) scattered by the environment **104**, and the laser field shown generally at **362**, for storing data representing the first signals **56**, produced in response to the laser beam **114** scattered by the environment. More particularly, in this embodiment the radar beam field **360** includes **512** successive two-byte sub-fields for storing **512** respective byte pairs, each byte pair representing a respective successive digital sample of the second signals **58**, and the laser field **362** includes **512** successive one-byte sub-fields for storing **512** respective single bytes, each byte representing a respective successive digital sample of the first signals **56**. In the present embodiment the data store **332** is used to generate and temporarily store a data structure such as that shown at **334**, which is then stored in the memory device **52** as a block of the data **302**.

In the present embodiment the measurement routine **308** also directs the processor circuit **54** to define further registers in the RAM **330**, including a display buffer **370**, and a timing register **371**. The display buffer may be used to control the display device **94** to display a representation of the data

representing the first signals **56** and/or the second signals **58** if desired. The timing register in the present embodiment is used by the processor circuit **54** as a calculation area for the purpose of generating timing signals at various frequencies in response to master timing signals.

Similarly, in this embodiment the analysis routine **320** directs the processor circuit **54** to define further registers and stores in the second memory device **329**, including a first return height store **372**, a first return grid store **373**, a ground return height store **374**, a relative foliage height store **375**, a ground grid store **376**, a foliage grid store **377**, a subterranean data store **378**, an assembled data store **379**, a migrated data store **381** and a tie lines region **383**. The first return height store **372** is used to store numerical representations of the height of highest portions of the environment **104**, relative to a geoid, produced in response to the laser data stored in the laser fields **362** of the data **302**, and the first return grid store **373** is used to store similar data formatted into a grid. The ground return height store **374** is used to store numerical representations of the height of the ground level of the environment relative to the geoid, produced in response to the radar data stored in the radar beam fields **360** of the data **302**. The relative foliage height store **375** is used to store numerical representations of the height of foliage of the environment relative to ground level of the environment, produced in response to both the laser and radar data. Similarly, the ground grid store **376** and the foliage grid store **377** are used to store similar data formatted into a grid. The subterranean data store **378** is used to store a numerical representation of a subterranean region of the environment **104**. The assembled data store **379** is used to store intermediate radar data for use in producing such representations. The migrated data store **381** is used to store data representing the second signals **58**, to which a migration algorithm has been applied by a representation processing circuit. The tie lines region **383** includes a plurality of stores corresponding to the various other stores

described in this paragraph, for storing data corresponding to a set of tie lines flown by the aircraft **100**, substantially perpendicular to the main flight lines flown by the aircraft.

In this embodiment, the CPS **60** further includes a timing device shown generally at **380**, for producing the master timing signals. More particularly, in this embodiment the timing device **380** includes a clock **382**, which in this embodiment is an oven-controlled crystal oscillator (OCXO) available from MTI-Milliren Technologies, Inc. of Newbury Port, Massachusetts, USA, which produces a **10** MHz clock signal, accurate to one part in 10^{10}. Alternatively, however, any other suitable type of clock, such as an atomic clock or other crystal oscillators for example, may be substituted. The clock **382** supplies the **10** MHz clock signal to the processor circuit **54**, via an I/O system shown generally at **390**. In addition, in this embodiment the clock **382** supplies the **10** MHz clock signal to a multiplier **384**, to the oscillator **260** shown in Figure **7**, and to the GPS device **80** shown in Figure **2**.

In the present embodiment, the multiplier **384** includes a **50**X multiplier, constructed in the usual manner from phase-lock loop modules. The multiplier **384** receives the **10** MHz clock signal from the clock **382**, in response to which it produces a signal having fifty cycles for each cycle of the **10** MHz clock signal. In other words, the multiplier **384** produces a **500** MHz clock signal, in response to, and synchronized with, the **10** MHz clock signal produced by the clock **382**. The multiplier **384** supplies the **500** MHz clock signal to the processor circuit **54**, via the I/O system **390**.

In addition, the multiplier **384** supplies the **500** MHz clock signal to an analog-to-digital converter (ADC) shown generally at **400**. In this embodiment, the ADC is operable to digitize the first and second signals **56** and **58**. More particularly, with respect to the second signals **58**, the ADC is operable to

digitize frequency-shifted signals received from the I-channel and Q-channel exit ports **278** and **288** shown in Figure **7**. In the present embodiment the ADC **400** includes a digitizer capable of sampling at a rate of **500** MS/s. The ADC **400** preferably has a phase jitter of less than **50** ps over a **10** s period and less than **200** ps over a **10** minute period, is capable of operating accurately at ambient temperatures of at least **27**°C (**80**°F), and preferably produces no detectable drop-outs (failures to take a sample). In the present embodiment, the ADC **400** includes a Cougar-**1000** digitizer available from Acqiris Asia-Pacific of Surrey Hills, Australia, from Acqiris USA of Monroe, NY, USA, or from Acqiris Europe of Geneva, Switzerland. Alternatively, however, other suitable digitizers are available from various manufacturers worldwide and may be substituted.

More particularly, referring to Figures **2**, **3**, **4**, **5**, **7**, **8a** and **8b**, in this embodiment the ADC **400** is capable of simultaneously receiving four separate analog channels of bandwidths up to **250** MHz at four respective input ports **402**, **404**, **406** and **408**, digitizing each such channel at a sampling rate of **500** MS/s, and producing corresponding digital data signals at respective output ports **410**, **412**, **414** and **416**. In this embodiment, only three such channels are used.

More particularly, in this embodiment the first input port **402** of the ADC **400** is in communication with the detector **122** shown in Figure **5**, for receiving the first signals **56** produced in response to the laser beam **114** scattered by the environment **104**. The second and third input ports **404** and **406** are in communication with the radar system **64**, for receiving the second signals **58** produced in response to the radar beam **106** scattered by the environment **104**. More particularly, in this embodiment the input port **404** is in communication with the I-channel exit port **278** of the radar reception system **68** shown in Figure **6** for receiving the I-channel signals of the second signals

58, and the third input port **406** is in communication with the Q-channel exit port **288** of the radar reception system for receiving the Q-channel signals of the second signals. The ADC **400** samples such signals on each of the above three channels at **500** MS/s, by producing an **8**-bit digital representation of the amplitude of the sampled signal at each sampling interval.

In this embodiment the ADC **400** further includes an internal memory **418**, which in this embodiment is capable of buffering or storing **128,000** such samples. The ADC **400** produces digital data signals at the output ports **410**, **412** and **414**, representing the first signals **56**, the I-channel component of the second signals **58**, and the Q-channel component of the second signals **58**, respectively. These digital data signals are communicated to the processor circuit **54**, via the I/O system **390**.

In this embodiment, the I/O system **390** includes a high-speed I/O device **420** in communication with the ADC **400**, the clock **382**, the multiplier **384**, and also with the laser **120** shown in Figure **5**, the UWB transmitter **144** shown in Figure **6**, and with the blanker **190** and the oscillator **260** shown in Figure **7**. More particularly, in this embodiment the high-speed I/O device **420** includes a PXI bus, in accordance with the PXI (PCI eXtensions for Instrumentation) specification.

In addition, in the present embodiment the I/O system **390** includes a low-speed I/O device **422**, which in this embodiment includes a low-speed I/O buffer, in communication with the GPS device **80** and the manual input device **90** shown in Figure **2**, and with the gain monitor connection **220** shown in Figure **7**. Alternatively, other types of high-speed I/O devices, low-speed I/O devices, and/or I/O systems may be substituted.

<u>OPERATION</u>

Measurement

Referring to Figures **2** through **9**, the measurement routine is shown generally at **308** in Figure **9**. Generally, the measurement routine **308** includes a plurality of blocks of codes which configure the processor circuit **54** to receive the first signals **56** produced in response to the laser beam **114** scattered by the environment **104**, to receive the second signals **58** produced in response to a radar beam scattered by the environment (which in this embodiment is the radar beam **106** scattered by the environment), and to store the data **302** representing the first and second signals in the memory device **52**, for use in producing a representation of the environment.

In this embodiment, execution of the measurement routine **308** is commenced in response to manual user input from the manual input device **90**. In the present embodiment, to measure the environment **104**, an operator of the aircraft **100** typically flies a number of substantially parallel flight lines over the environment at a substantially uniform altitude above a geoid, each of which may be **10** km long for example, over the environment, during which the environment is measured. In addition, to provide improved analytical results, in the present embodiment the aircraft **100** also flies a number of tie lines, substantially perpendicular to and intersecting the flight lines. Accordingly, in this embodiment a user of the system **50** typically awaits confirmation, either from the operator of the aircraft **100** or from monitoring navigation instruments, that the aircraft **100** has commenced its flight along a given flight line or tie line, in response to which the user actuates the manual input device **90** to commence execution of the measurement routine. Alternatively, however, other measurement techniques may be substituted, and similarly, the measurement routine may be automatically executed if desired.

In the present embodiment, the measurement routine **308** commences with a first block of codes **450** shown in Figure **9**, which directs the processor circuit **54** to commence execution of the timing thread **310**. In this embodiment, the timing thread directs the processor circuit to receive the **10** MHz and **500** MHz clock signals from the clock **382** and the multiplier **384** shown in Figure **8a**, and to count the number of cycles in such signals, in order to effectively act as a divider to produce at least one synchronized lower-frequency timing signal for use in controlling various other components of the system **50**. More particularly, in this embodiment, in response to the **10** MHz clock signal from the clock **382**, the timing thread **310** directs the processor circuit to produce a **150** Hz timing signal for use in triggering the laser system **62**, the radar transmission system **66**, the blanker **190** of the radar reception system **68**, and the ADC **400**. In the present embodiment the timing thread **310** also directs the processor circuit to synchronize an internal system clock (not shown) of the central processing system with the clock **382**.

Referring to Figures **3**, **4**, **5**, **8a**, **8b**, **9**, **10** and **11**, block **460** then directs the processor circuit **54** to cause the first signals **56** to be produced in response to the laser beam **114** scattered by the environment **104**, and to store data **302** representing the first signals in the memory device **52**. To achieve this, in the present embodiment the processor circuit **54** monitors the **10** MHz clock signal received from the clock **382**, the **500** MHz signal received from the multiplier **384**, and also monitors the **150** Hz timing signal which the processor circuit produces under the direction of the timing thread **310** in response to the **10** MHz clock signal.

Referring to Figures **3**, **5**, **8a**, **8b**, **9** and **10**, in this embodiment, block **460** first directs the processor circuit **54** to operate the laser **120** to produce, as the incident laser beam **112**, an incident laser pulse having a duration on the order of one nanosecond, for scattering by the environment to produce

scattered portions of the laser pulse. More particularly, in the present embodiment, **75** times per second, at the commencement of every even-numbered cycle of the **150** Hz timing signal (in other words, once every **133,333.33** cycles of the **10** MHz clock signal; for example, at t = **0** s, **0**.**0133**s, **0**.**0267**s, etc.) block **460** directs the processor circuit **54** to control the I/O system **390** to transmit a triggering signal, such as that shown at **462** in Figure **10**, to the laser **120** shown in Figure **5**. More particularly, in this embodiment the I/O system **390** further includes a standard commercially available high-speed transistor-transistor logic (TTL) chip (not shown) operable to produce triggering signals having sub-nanosecond rise times. Alternatively, any other devices operable to produce fast rise-time triggering signals, such as a complementary metal oxide semiconductor (CMOS) chip or a macroscopic resistor-capacitor (RC) circuit configuration for example, may be substituted for the TTL chip. In this embodiment, block **460** directs the processor circuit to control the TTL chip of the I/O system **390** to produce the triggering signal **462** to have a duration **464** on the order of one nanosecond. More particularly, in this embodiment the duration **464** of the triggering signal **462** is two nanoseconds (one complete cycle of the **500** MHz clock signal). The **2** ns triggering signal **462** causes the laser **120** to transmit to the environment, as the incident laser beam **112**, a laser pulse of approximately **2** ns in duration. Due to the operation of the motion mechanism **128** of the laser system **62** as described earlier herein, the incident laser beam **112** is directed vertically downward from the aircraft **100** toward the environment **104**.

Block **460** then directs the processor circuit **54** to continue monitoring the **10** MHz clock signal from the clock **382**, until a pre-defined delay **466** has elapsed. More particularly, in this embodiment the delay **466** is equal to **1.2** microseconds (**12** cycles of the **10** MHz clock signal).

In this regard, it will be appreciated that the aircraft **100** will typically be flying at a safe height above the highest foliage, projections or other uppermost portions of the environment **104**. For example, if the aircraft **100** is flying at an average altitude of **300** m (**1000** ft) AGL, there will generally not be any foliage or other projections higher than **120** m AGL. Accordingly, in this example, during the first **1.2** μs microseconds (the hypothetical return travel time for the laser beam **112** to travel **180** m down and back) following the generation of the incident laser beam **112** in response to the triggering pulse **462**, there is no need to produce and store data in response to any signals produced by the detector **122** of the laser system **62**, as any such signals are produced in response to optical noise rather than the laser beam **114** scattered by the environment **104**.

As the incident laser beam **112** strikes the environment **104**, the environment scatters the incident laser beam to produce the laser beam **114** scattered by the environment. A short time following the delay **466**, the detector begins to receive the laser beam **114** scattered by the environment, and begins to produce the first signals **56** in response thereto.

More particularly, referring to Figure **11**, at any given instant in time, there may be a plurality of portions **467** of the environment **104** directly beneath the aircraft **100**, such as an upper portion **468**, intermediate portions **470** and **472** and a lower portion **474** for example. In this embodiment the upper and intermediate portions include light foliage, while the lower portion **474** includes ground level. In some circumstances, for example, if the foliage portions are relatively sparse or bare tree branches and twigs, the upper portion **468** may permit at least some of the incident laser beam **112** to pass through to the intermediate and lower portions of the environment, and may similarly permit scattered portions **476** of the resulting laser beam **114** scattered by such lower portions of the environment to return to the aircraft **100** for detection.

For example, as shown in Figure **11**, the scattered portions **476** produced by the environment in response to the incident laser pulse may include scattered portions **478**, **480**, **482** and **484**, scattered by the respective portions **468**, **470**, **472** and **474** of the environment **104**.

Accordingly, referring back to Figures **5**, **8a**, **8b**, **9**, **10** and **11**, in this embodiment block **460** configures the processor circuit **54** to cooperate with a detection system, to continuously produce the data **302** in response to the scattered portions **476** of the laser pulse (i.e. the laser beam **114**) scattered by the respective portions **467** of the environment **104**, during a measurement interval of sufficient duration to receive all the scattered portions **476**. More particularly, in this embodiment the detection system includes the detector **122**, which is operable to receive the scattered portions **476** and to produce (as the first signals **56**) analog signals in response thereto. The detection system further includes the ADC **400**, and block **460** directs the processor circuit **54** to operate the ADC **400** to cooperate with the detector **122** to continuously produce digital signals in response to the analog signals, during the measurement interval.

More particularly, at the end of the **1.2** µs delay **466** shown in Figure **10**, block **460** directs the processor circuit **54** to control the TTL chip of the I/O system **390** to transmit a triggering signal to the ADC **400** shown in Figure **7**, to effectively define a measurement window such as that shown at **490 in** Figure **10**, having a duration or measurement interval **492** of at least on the order of one microsecond. More particularly still, in this embodiment this triggering signal is similar to the triggering signal **462**, and in response to receiving a leading edge of the triggering signal, the ADC **400** is pre-programmed to take **512** samples of the first signals **56** at its sampling rate of **500** MS/s. Thus, in this embodiment the measurement interval **492** is **1.024** microseconds.

In this regard, in the present embodiment, and in the present example, wherein the aircraft **100** is flying at an average altitude of **300**m AGL, it will be appreciated that the longest possible return time of the laser is the ground return time, i.e. the time required to detect the scattered portion **484** scattered by the lower portion **474** of the environment, which at an altitude of **300** m is **2** microseconds. Thus, as the measurement interval **492** commences **1.2** μs after transmission of the incident laser beam **112** (before any scattered portions of the laser pulse are able to arrive at the detector **122**), and ends **1.024** microseconds later (after the last such scattered portion has arrived at the detector **122**), the measurement interval **492** in the present embodiment is sufficient for all of the scattered portions **476** to be received by the detector **122**.

In this embodiment, the detector **122** receives the scattered portions **476** of the laser beam **114** scattered by the respective portions **467** of the environment **104**, in response to which the detector **122** produces the first signals **56**, or more particularly, analog electrical signals whose voltage varies in proportion to the intensity of the received scattered portions **476** of the laser beam **114**.

The ADC **400** receives the first signals **56** in their analog form from the detector **122** at the input port **402**, and simultaneously receives the **500** MHz clock signal from the multiplier **384**. Upon receiving a leading edge of the triggering signal from the I/O system **390**, the measurement window **490** commences, during which the ADC digitizes the first signals **56**, by sampling the first signals **56** at a rate of **500** MS/s. More particularly, each sample produced by the ADC **400** includes an **8**-bit digital representation of the voltage of the first signals **56** arriving at the input port **402**. The ADC **400** temporarily stores each such sample in the internal memory **418**. In addition, the ADC **400** transmits the first signals **56** in digital format to the processor

circuit **54**, or more particularly, transmits digital electrical signals representing the **8**-bit samples temporarily stored in the internal memory **418** to the processor circuit via the high-speed I/O device **420**. The ADC **400** continues to sample the signals arriving at the input port **402** in this manner, until **512** such samples have been taken, at which point the ADC ceases such sampling.

In this embodiment, block **460** directs the processor circuit **54** to receive the first signals **56** in their digital format from the ADC **400**, and to store data representing the digital signals in the second memory device **329**, which in this embodiment is the RAM **330**. More particularly, block **460** directs the processor circuit to define, in the second memory device **329**, the data structure **334** including the measurement context field **336** for storing measurement context information, the laser field **362** for storing the data representing the first signals **56**, and the radar beam field **360** for storing the data representing the second signals **58**. Block **460** then directs the processor circuit **54** to store **512** bytes in response to the digital signals received from the ADC **400**, in successive entries in the laser field **362** of the data structure **334**, each byte representing a corresponding **8**-bit sample produced by the ADC.

In this embodiment, block **460** further directs the processor circuit **54** to store measurement context information in the second memory device **329** in association with the data representing the first signals **56**.

More particularly, in this embodiment, block **460** directs the processor circuit **54** to store, as the measurement context information, global positioning satellite (GPS) information indicative of a location at which at least one of the laser beam and the radar beam (in this case, the laser beam **114**) is received. To achieve this, block **460** directs the processor circuit to receive data signals

produced by the GPS device **80** representing the present position and velocity of the aircraft **100** and the present time, via the low-speed I/O device **422**, and to store data representing the position and present time in the GPS field **338** of the data structure **334**. In this regard, as the GPS information in the present embodiment is updated only twice per second, whereas radar and laser measurements are each obtained **75** times per second, the GPS information provides an approximation of the measurement location. However, as discussed in greater detail below, the GPS measurements may be further processed to interpolate more accurate position data indicative of the measurement location.

Similarly, in this embodiment block **460** directs the processor circuit to store, as the measurement context information, user-inputted information. More particularly, in this embodiment the user-inputted information includes a flight line indication indicative of a flight line over which the laser beam and the radar beam are received by an airborne environment measurement system. To achieve this, block **460** directs the processor circuit to monitor signals from the low-speed I/O buffer produced in response to new manual input at the manual input device **90**, and to update the contents of the manual data sub-field **342** of the data structure **334** if necessary.

In addition, in this embodiment block **460** directs the processor circuit **54** to store, as the measurement context information, at least one time value indicative of a time at which at least one of the laser beam and the radar beam (in this case, the laser beam **114**) is received. To achieve this, block **460** directs the processor circuit to update a current time value stored in the time sub-field **350** of the data structure **334**, in response to signals produced by the internal system clock (not shown) which is synchronized with the clock **382**.

In this embodiment, for the purpose of a data structure containing laser data, it is not necessary to update the contents of the gain monitoring sub-field **340**. In addition, although the GPS and manual sub-fields **338** and **342** have been described as being updated with each new data structure, alternatively, such sub-fields may be updated less frequently. In this regard, in the present embodiment each successive data structure is generated every **1/150**th of one second, whereas new GPS data is obtained only twice per second, and accordingly, strictly speaking, it is not necessary to store GPS data any more frequently than it is obtained. Moreover, even if GPS information were obtained more frequently, during the **1/150**th of one second between generation of successive data structures, the aircraft **100** is likely to travel approximately one-half meter, and accordingly, the change in GPS position data will typically be less than the error bars surrounding such position data. Similarly, lower updating rates, such as **10** Hz for example, are generally adequate for updating manually-entered data.

Block **460** then directs the processor circuit **54** to store the data produced in response to the scattered portions **476** of the laser pulse (laser beam **114**) scattered by the respective portions **467** of the environment **104**, in the memory device **52**, for use in producing a representation of the environment.

More particularly, block **460** directs the processor circuit to store the data structure **334** as a new corresponding data structure **500** in the memory device **52**, as the data **302**. If the data **302** already contains previously generated data structures, block **460** directs the processor circuit to append the new data structure **500** to the data **302**, contiguously to the most recently stored existing data structure of the data **302**. Thus, in this embodiment, the data **302** includes a plurality of contiguous successively-generated data structures such as the data structure **334**.

Block **460** then directs the processor circuit to clear the contents of the laser field **362** of the data structure **334** in the second memory device **329**, for generation of the next successive data structure.

Referring to Figures **3**, **4**, **6**, **7**, **8a**, **8b**, **9**, **10** and **11**, block **510** then directs the processor circuit **54** to cause the second signals **58** to be produced in response to a radar beam scattered by the environment (which in this embodiment is the radar beam **106** scattered by the environment), and to store data **302** representing the second signals in the memory device **52**.

In this embodiment, block **510** first directs the processor circuit **54** to operate the radar transmission system **66** shown in Figure **6** to produce, as the incident radar beam **102**, an incident radar pulse having a duration on the order of one nanosecond, for scattering by the environment to produce the radar beam **106** scattered by the environment, which in this embodiment includes scattered portions of the radar pulse scattered by respective portions of the environment.

More particularly, in the present embodiment, **75** times per second, at the commencement of every odd-numbered cycle of the **150** Hz timing signal produced by the processor circuit **54** under the direction of the timing thread **310** (in other words, once every **133,333.33** cycles of the **10** MHz clock signal produced by the clock **382**; for example, at t = **0.0067**s, **0.02**s, **0.0333**s, etc.) block **460** directs the processor circuit **54** to control the I/O system **390** to transmit a triggering signal, such as that shown at **511** in Figure **10**, to the radar transmission system **66** shown in Figure **6**. In this embodiment, the triggering signal **511** has a duration of approximately **3.3** ns (i.e., approximately **1.67** cycles of the **500** MHz clock signal produced by the multiplier **384**). The **3.3** ns triggering signal **511** causes the UWB transmitter **144** to generate a **10** kV unipolar impulse signal to cause the transmission antenna system **108** to produce, as the incident radar beam **102**, a UWB radar pulse ranging from **200**

MHz - **400** MHz and having a duration of approximately **3.3** ns (i.e., one complete cycle at the center frequency of **300** MHz), as described above in connection with the radar transmission system, and to direct the incident radar beam **102** to the environment **104**.

In addition, it will be recalled that in the present embodiment the receiver **150** is configured to receive low-amplitude signals, and accordingly, it is desirable to protect the receiver **150** against possible overload from much higher-amplitude signals that may tend to be produced by the reception antenna system **110** shown in Figure **7** if the reception antenna system inadvertently receives a portion of the incident radar beam **102** directly from the transmission antenna system **108**. Accordingly, in this embodiment, prior to the transmission of the triggering signal **511** to the radar transmission system **66**, block **510** directs the processor circuit **54** to transmit a triggering signal, such as that shown at **514** in Figure **10**, to the blanker **190** to cause the blanker to blank or block signals produced by the reception antenna system **110**. More particularly, in this embodiment block **510** directs the processor circuit to begin transmitting the triggering signal **514** to the blanker **190** approximately **100** ns (one cycle of the **10** MHz clock signal) prior to the transmission of the triggering signal **511** to the radar transmission system, and to continue transmitting the triggering signal **514** for approximately **200** ns (two cycles of the **10** MHz clock signal) thereafter, to define a blanking interval of sufficient duration to prevent any transmitter cross-talk signals produced in response to directly received portions of the incident radar beam from reaching the receiver **150**, effectively excising any radar transmission resonance around the aircraft **100**.

Block **510** then directs the processor circuit **54** to continue monitoring the **10** MHz clock signal from the clock **382**, until a pre-defined delay **516** has elapsed following the transmission of the triggering signal **511**. More particularly, in this embodiment the delay **516** is equal to **1.2** μs (**12** cycles of

the **10** MHz clock signal), for the same reasons as those discussed above in connection with block **460**.

As the incident radar beam **102** strikes the environment **104**, the environment scatters the incident radar beam to produce the radar beam **106** scattered by the environment. A short time following the delay **516**, the detector begins to receive the radar beam **106** scattered by the environment, and begins to produce the second signals **58** in response thereto.

More particularly, referring back to Figure **4**, as discussed above in connection with the laser system, at any given instant in time, there may be a plurality of portions **467** of the environment **104** directly beneath the aircraft **100**, including the upper portion **468** and the intermediate portions **470** and **472**, which in this example are all foliage, the lower portion **474** which in this example is ground level, and a subterranean portion shown generally at **518**. In this embodiment, portions of the incident radar beam **102** tend to be scattered by the respective portions **467** of the environment. In particular, although the higher frequencies (in the vicinity of **400** MHz) of the incident radar beam **102** provide greater resolution than longer frequencies, these high frequencies are more significantly scattered by the upper and intermediate portions of the environment than lower frequencies of the incident radar beam. Conversely, although the longer wavelengths (in the vicinity of **200** MHz) of the incident radar beam **102** result in lower resolution, these longer wavelengths penetrate deeper into the environment **104**, generally penetrating into the subterranean portion **518**, which scatters portions of the incident radar beam back up through the environment to the aircraft **100** for detection thereat. Thus, in this embodiment, the radar beam **106** scattered by the environment includes scattered portions shown generally at **520** of the incident radar pulse, such as scattered portions **522**, **524**, **526** and **528** for example, scattered by the respective portions **467** of the environment **104**.

Accordingly, referring back to Figures **7**, **8a**, **8b**, **9**, **10** and **11**, in this embodiment block **510** the processor circuit **54** to operate an airborne radar reception system to continuously produce data signals in response to the scattered portions **520** of the radar pulse (i.e. the radar beam **106**) scattered by the respective portions **467** of the environment **104**, during a measurement interval of sufficient duration to receive all the scattered portions **520**. In this embodiment the airborne radar reception system includes the radar reception system **68**, which acts as a detector operable to receive the scattered portions **520** and to produce analog signals in response thereto, and further includes the ADC **400**, which is operable to cooperate with the detector to continuously produce digital signals in response to the analog signals, during the measurement interval.

More particularly, to achieve this in the present embodiment, at the end of the **1.2** μs delay **516** shown in Figure **10** following transmission of the triggering signal **511** to the radar transmission system **66**, block **510** directs the processor circuit **54** to control the TTL chip of the I/O system **390** to transmit a triggering signal to the ADC **400** shown in Figure **7**, to define a measurement window such as that shown at **530** in Figure **10**, having a duration or measurement interval **532** of at least on the order of one microsecond. More particularly still, in this embodiment the triggering signal is similar to the triggering signal **462**, and in response to receiving a leading edge of the triggering signal, the ADC **400** is pre-programmed to take **512** samples of the second signals **58** at its sampling rate of **500** MS/s. Thus, in this embodiment the measurement interval **532** is **1.024** microseconds. In this regard, in the present embodiment, and in the present example, wherein the aircraft **100** is flying at an average altitude of **300**m AGL, it will be appreciated that the combined delay **516** of **1.2** μs and the further **1.024** μs measurement interval **532** provides for a total return time of **2.224** μs, which allows scattered portions **520** of the radar beam **106** scattered by respective portions of the

environment as deep as **330** m below the aircraft **100**, or in other words about **30** m below ground level in the present example, to be received at the aircraft **100**. As significant returns are usually not obtained from depths greater than **30** m below ground, the measurement interval **532** is effectively sufficient for all of the scattered portions **520** to be received.

Referring to Figures **4**, **7**, **8a**, **8b**, **9** and **10**, in this embodiment, the reception antenna system **110** receives the scattered portions **520** of the radar beam **106** scattered by the respective portions **467** of the environment **104**, in response to which the reception antenna system **110** produces the second signals **58**, or more particularly, analog electrical signals at frequencies of the scattered portions **520** (in this embodiment, **200** MHz - **400** MHz), whose voltage varies in proportion to the intensity of the received scattered portions **520** of the radar beam **106**.

In this embodiment the second signals **58** are then propagated through the blanker **190** and the receiver **150**, as described above in connection with the radar reception system **68** shown in Figure **7**. In particular, in the present example, in which the aircraft **100** is flying at an average altitude of **300** m AGL, a user of the system **50** actuates the manual gain control device **218** shown in Figure **7**, to cause the RF gain control device **212** to control the attenuator **204** to transmit the second signals **58** therethrough with **0** dB attenuation (i.e., no attenuation). The frequency-shifter **227** then frequency-shifts the **200** to **400** MHz second signals **58** by **-300** MHz and divides the second signals **58** into in-phase frequency-shifted signals supplied at the I-channel exit port **278**, and in-quadrature frequency-shifted signals supplied at the Q-channel exit port **288**, each at baseband to **100** MHz frequencies, as described in greater detail above in connection with the receiver **150** shown in Figure **7**.

In this embodiment, the second signals **58**, or more particularly the I-channel and Q-channel signals produced at the exit ports **278** and **288** respectively of the receiver **150**, are received at the input ports **404** and **406** respectively of the ADC **400** shown in Figure **7**. The ADC **400** simultaneously receives the **500** MHz clock signal from the multiplier **384**. Upon receiving a leading edge of the triggering signal from the I/O system **390**, the measurement window **530** commences, during which the ADC digitizes the second signals **58**, by sampling the I-channel signals at a rate of **500** MS/s while simultaneously sampling the Q-channel signals at the same rate. More particularly, each I-channel sample produced by the ADC **400** includes an **8**-bit digital representation of the voltage of the I-channel signals arriving at the input port **404**, and similarly, each Q-channel sample includes an **8**-bit representation of the voltage of the signals arriving at the input port **406**. The ADC **400** temporarily stores the I-channel samples in a first area of the internal memory **418** corresponding to the input port **404**, and temporarily stores the Q-channel samples in a second area of the internal memory corresponding to the input port **406**. In addition, the ADC **400** transmits the second signals **58** in digital format to the processor circuit **54**, or more particularly, transmits first and second respective digital electrical signals representing the **8**-bit I-channel and Q-channel samples temporarily stored in the internal memory **418** to the processor circuit via the high-speed I/O device **420**. The ADC **400** continues to sample the signals arriving at the input ports **404** and **406** in this manner, until **512** such I-channel and Q-channel sample pairs have been taken, at which point the ADC ceases such sampling.

Referring to Figures **8a**, **8b** and **9**, in this embodiment, block **510** further directs the processor circuit **54** to store, as the data representing the second signals, an in-phase value and an in-quadrature value representing an in-phase component and an in-quadrature component respectively of the second signals. To achieve this, block **510** directs the processor circuit to receive the

second signals **58** in their digital format from the ADC **400**, and to store data representing the digital signals in the second memory device **329**, which in this embodiment is the RAM **330**. In this regard, the data structure **334** in which the data is to be stored has been previously defined in the RAM by the processor circuit at block **460** above, at which time the contents of the laser field **362** were reset following copying of the data structure **334** to the memory device **52**.

Block **510** directs the processor circuit **54** to store **1024** bytes in response to the digital signals received from the ADC **400**, in successive byte-pair entries in the radar beam field **360** of the data structure **334**. More particularly, in this embodiment the radar beam field **360** has a width of two bytes. Accordingly, in this embodiment block **510** directs the processor circuit **54** to store the **512** one-byte I-channel samples in the first eight bit locations of the **512** two-byte sub-fields of the radar beam field **360**, in the order in which such the digital signals representing such I-channel samples are received from the ADC **400**. Similarly, block **510** directs the processor circuit to store the **512** one-byte Q-channel samples in the second eight bit locations in the **512** sub-fields of the field **360**. Thus, in this embodiment, each of the **512** sub-fields of the radar beam field **360** is of the form (I, Q), wherein I and Q are **8**-bit digital representations of the **0** - **100** MHz I-channel and Q-channel signals simultaneously sampled by the ADC **400**. It will be appreciated that such a byte pair represents a sample of the entire -**100** MHz to +**100** MHz range of the frequency-shifted second signals **58**, as the byte pair represents a complex vector including a real component (the I-channel sample) and the imaginary component (the Q-channel sample).

In this embodiment, block **510** further directs the processor circuit **54** to store measurement context information in the second memory device **329** in association with the data representing the second signals **58**.

More particularly, in this embodiment, block **510** directs the processor circuit **54** to store, as the measurement context information, global positioning satellite (GPS) information and a time value indicative of a location and time respectively at which the radar beam (the radar beam **106**) is received, and user-inputted information, as described above in connection with block **460**.

In addition, as the data structure **334** includes radar data, in this embodiment block **510** configures the processor circuit to store, as the measurement context information, attenuation information indicative of an amount of attenuation of the second signals **58**. More particularly, in this embodiment block **510** directs the processor circuit **54** to monitor the signal received at the I/O system **390** from the gain monitor connection **220** shown in Figure **7**, whose voltage represents an amount of attenuation of the second signals **58** provided by the attenuator **204**. Block **510** directs the processor circuit to store a value representing this amount of attenuation in the gain monitoring sub-field **340**. Although the gain monitoring sub-field is updated with each new data structure containing radar data in the present embodiment, alternatively, the gain monitoring sub-field **340** may be updated less frequently if desired, as the manual gain control device **218** shown in Figure **7** will usually not be adjusted during the course of a given flight line.

Block **510** then directs the processor circuit **54** to store the data produced in response to the scattered portions **520** of the radar pulse (radar beam **106**) scattered by the respective portions **467** of the environment **104**, in the memory device **52**, for use in producing a representation of the environment. More particularly, block **510** directs the processor circuit to store the data structure **334** as a new corresponding data structure **534** in the memory device **52**, as the data **302**. In this embodiment, the data **302** already contains previously generated data structures, including the data structure **500** containing laser data as described above in connection with block **460**.

Accordingly, block **510** directs the processor circuit to append the new data structure **534** to the data **302**, contiguously to the most recently stored existing data structure **500** of the data **302**. Thus, in this embodiment, the data **302** includes a plurality of contiguous successively-generated data structures such as the data structure **334**.

Block **510** then directs the processor circuit **54** to clear the contents of the radar beam field **360** of the data structure **334** in the second memory device **329**, for generation of the next successive data structure.

Referring to Figures **2**, **8a**, **8b** and **10**, following execution of blocks **460** and **510**, block **540** directs the processor circuit to determine whether it is to cease execution of the measurement routine **308**. In the present embodiment, block **540** directs the processor circuit to monitor signals received at the I/O system **390** from the manual input device **90** shown in Figure **2**, to determine whether a user of the system **50** has entered an "end" command indicating that a given desired flight line measurement has been completed. If such a command is detected, the measurement routine **308** is ended. If no such command is received, the processor circuit is directed back to blocks **460** and **510**, to continue storing alternating data structures corresponding to the laser measurements performed at block **460** and the radar measurements performed at block **510** respectively, until the "end" command is detected at block **540**. Alternatively, however, if desired, the measurement routine **308** may configure the processor circuit to automatically commence and terminate in response to pre-determined conditions.

Referring to Figures **2**, **4**, **8a**, **8b** and **9**, if desired, the measurement routine **308** may further include an additional block of codes **550**, for directing the processor circuit **54** to produce a representation of the environment **104**, such as a representation **552** shown in Figure **2** for example. In this regard, for

some applications it may be desirable for a user of the system **50** to view a real-time representation of the environment **104** in response to the first signals **56** and/or the second signals **58**. Such a representation may be used for the limited purpose of verifying that the system **50** appears to be obtaining and storing useful data representing the first and second signals, for example. In this embodiment, block **550** directs the processor circuit to display, as the representation **552**, vertical traces **554** and **556** shown in Figure **2**, representing the data produced and stored in response to the first and second signals **56** and **58** respectively. In this embodiment, the vertical traces are produced in response to the sequential contents of the laser field **362** and the first eight bit positions of the electromagnetic beam field **360** of the two most recently produced data structures **334**, such as the data structures **500** and **502** stored in the memory device **52** for example. More particularly, in this embodiment block **550** directs the processor circuit to store data in the display buffer **370** to control the display device **94** to produce a scrolling display, with a new such vertical traces being displayed once per second at a right-hand region of the display device **94**, and gradually scrolling toward a left region of the display device to make room for the next such vertical traces. Alternatively, other real-time displays may be substituted, or such displays may be omitted entirely if desired.

Analysis

Referring to Figures **4**, **8a**, **8b**, **11**, **12** and **13**, the analysis routine is shown generally at **320** in Figure **12**. Generally, the analysis routine **320** configures a representation processing circuit **560** to use the data **302** to produce a representation of the environment **104**. For convenience of illustration, in the present embodiment the representation processing circuit **560** includes the processor circuit **54**. More generally, however, it is contemplated that the representation processing circuit **560** which executes the analysis routine **320**

will more often include a separate representation processing circuit, such as a microprocessor **562** shown in Figure **4**, which may be embodied in a ground-based computer based anywhere in the world such as a desktop computer **564**, for example. More generally still, although the analysis routine **320** described herein provides a number of examples of representations of the environment **104** that may be produced using the data **302** obtained by the system **50**, alternatively, such data may be used for producing any other type of representation, including any type of numerical, graphical, or imaging representation, for example.

In this embodiment, prior to execution of the analysis routine **320**, interpolated GPS information is first obtained, in order to provide more accurate indications of the measurement location of the aircraft **100** at which each radar or laser measurement represented by each respective stored data structure was obtained. In this regard, it will be recalled that in the present embodiment, GPS information obtained from the GPS device **80** is updated only twice per second, during which time **75** laser data structures and **75** radar data structures are produced. Accordingly, in this embodiment an interpolation routine (not shown) is executed to interpolate more accurate position information corresponding to each measurement location. Such an interpolation routine may include GRAPHNAV software available from Wavepoint of Calgary, Canada for example, although alternatively, any other suitable interpolation or curve-fitting algorithms may be used.

More particularly, in this embodiment, prior to execution of the analysis routine **320**, the data **302** in the memory **52** is first copied to an archive (not shown), to preserve the original raw data. (In embodiments where the representation processing circuit **560** is not the processor circuit **54**, such archiving may be unnecessary, as the data **302** will have been copied from the memory **52** to a separate hard drive or other medium accessible by the representation

processing circuit, and thus the memory **52** itself may serve as the archive, with all subsequent analysis and alternations being performed only on the data so copied.)

The interpolation routine then directs the representation processing circuit to sequentially address each set of data structures of the data **302** corresponding to a particular flight line, as identified by matching contents of the flight line sub-field **344** of each such data structure. For each addressed set of data structures corresponding to a given flight line, the interpolation routine directs the representation processing circuit to read the entire set of GPS data (x, y, z) stored in the GPS sub-fields **338** of the addressed set of data structures, and to produce and store interpolated position data (x, y, z) in the GPS sub-field **338**. In this embodiment, the interpolated position data overwrites the contents of the GPS sub-field **338** of the addressed data structures of the data **302** (it will be recalled that the original raw data has been separately archived, and is therefore not lost by such overwriting). The interpolation routine directs the representation processing circuit to repeat such interpolation for each flight line flown by the aircraft **100**, until the GPS sub-fields of the data structures of all of the data **302** contain more accurate, interpolated position data (x, y, z) indicative of the actual position of the aircraft **100** at the time the measurement represented by each such data structure was obtained.

If desired, in embodiments where differential GPS is employed, the interpolation routine may also direct the representation processing circuit to receive a “dot out file”, including GPS data obtained at the same times as the aircraft GPS data, at a separate ground station whose location is known, and may compare such information to the known location of the ground station to produce an error correction, which is then applied to correct the interpolated position data.

Once such interpolated position data has been produced for all laser and radar data structures of the data **302**, the analysis routine **302** is then executed.

In this embodiment, the analysis routine **320** begins with a first block of codes **600**, which directs the representation processing circuit **560** to analyze the laser data produced in response to the first signals **56**. More particularly, in this embodiment block **600** directs the representation processing circuit **560** to identify a foliage height of the environment **104**. In this regard, although radar data may also be used to identify the foliage height of the environment, it has been found that laser data is more accurate for this purpose.

Referring to Figures **4** and **11**, it will be appreciated that if the environment **104** includes foliage above its ground level immediately beneath the aircraft when laser data is obtained as described above, then the scattered portion **478** of the incident laser pulse, scattered by the upper portion **468** of the environment, is the first scattered portion of the laser pulse to be received by the system **50**, which produces a first return portion **602** of the first signals **56** in response thereto. If the foliage is fairly light, such as the situation shown in Figure **11** for example, then further portions **604** of the first signals will be generated in response to additional scattered portions, such as those shown at **480**, **482** and **484** for example, received at the system **50**. However, if the foliage is thick, such as the situation shown in Figure **2** for example, then the first return portion **602** of the first signals **56** is typically the only portion of the first signals **56** that is appreciably above noise level. Similarly, if there is no foliage at all between the aircraft **100** and the ground level of the environment, the first return portion **602** of the first signals **56** is produced in response to the scattered portion **484** of the laser pulse scattered by the lower portion **474**, i.e. the ground level, of the environment.

Referring to Figures **4**, **8a**, **8b**, **12** and **13**, in this embodiment block **600** first directs the representation processing circuit **560** to address the first set of data structures of the data **302** corresponding to the next flight line which has not yet been analyzed by the representation processing circuit **560**. More particularly, block **600** directs the representation processing circuit to read the contents of the flight line sub-field **344** of the manual data sub-field **342** of each of the data structures stored as the data **302** in the memory device **52**, to identify all such data structures corresponding to the next unanalyzed flight line (such as flight line **#1** in the case of the first time block **600** is executed by the representation processing circuit, for example), having laser data stored in their laser field **362**. In this embodiment, in which each flight line is approximately **10** km long, the system **50** produces approximately **10,000** data structures containing laser data corresponding to locations approximately **1** meter apart along each flight line.

Block **600** then directs the representation processing circuit **560** to sequentially address each such identified data structure, and for each addressed data structure, block **600** directs the representation processing circuit to produce a position value P representing the position of the first of the **512** one-byte sub-fields of the laser field **362** of the addressed data block having contents exceeding a pre-defined threshold noise value representing a maximum likely noise value produced by the detector **122** of the laser system. For example, if the first **117** sub-fields of the laser field **362** contain values less than the noise value and the **118**th sub-field contains a value exceeding the noise value, the representation processing circuit produces a value P = **118**.

In this embodiment, block **600** then directs the representation processing circuit **560** to read the interpolated aircraft position information stored in the

GPS sub-field **338** of the currently addressed data structure, and to produce a first return height value R_1, as follows:

$$R_1 = z_{GPS} - 0.5c[t_{DEL} + (t_{SAM})(P)] \qquad \textbf{(3)}$$

wherein

R_1 = the first return height of the environment **104**, or in other words, the height of the highest portion of the environment **104** in meters at the location corresponding to the currently addressed data structure, relative to a geoid;

Z_{GPS} = the height of the aircraft **100** in meters, relative to the geoid, at the location of the laser measurement, as obtained from the GPS sub-field **338** of the currently addressed data structure;

c = the speed of light in meters per second

t_{DEL} = the time delay in seconds following the transmission of the incident laser beam **112** prior to commencing sampling and storing data in the laser field **362** representing the first signals **56** (in this embodiment, t_{DEL} =**1.2** x **10**$^{-6}$ s);

t_{SAM} = the sampling period in seconds between successive samples of the first signals **56** stored in respective successive sub-fields of the laser field **362** (in this embodiment, t_{SAM} = **2.0** x **10**$^{-9}$ s); and

P = the position value (**1** $\leq$ P $\leq$ **512**) representing the position of the first sub-field of the laser field **362** containing a value greater than maximum expected noise.

Block **600** then directs the representation processing circuit **560** to store a set of values of the form (x, y, R_1) in the first return height store **372** in the RAM

330, wherein (x, y) are interpolated latitudinal and longitudinal coordinates to which the currently addressed data structure corresponds, obtained from the GPS sub-field **338** of the data structure, and R_1 is the first return height as described above.

Block **600** then directs the representation processing circuit **560** to repeat the above procedures for each of the addressed data structures corresponding to the particular flight line currently being analyzed, to produce and store a complete set of values (x, y, R_1) for the current flight line. In addition to storing such values in the first return height store **372**, block **600** directs the representation processing circuit to copy such values to a corresponding first return height store **606** of an analyzed data region **605** of the memory device **52**, which in this embodiment includes respective stores corresponding to each of the various stores of the second memory device **329** which store analyzed data produced by the representation processing circuit under the direction of the analysis routine.

Although the foregoing identification of the first return height from the laser data suffices for the analysis routine **320** of the present embodiment, alternatively, for other applications, it may be desirable to produce and store sets of values of the form (x, y, R_1, R_2, R_3, ... R_N), wherein R_1 ... R_N are obtained in the same manner as R_1 above and represent all return heights of the environment for which the value stored in the corresponding sub-field of the laser field **362** exceeded noise, in order to provide laser data over a full swath potentially ranging from a highest foliage height to ground level. Such complete data may be particularly useful for light foliage environments, for example, and may be used to produce various representations of the environment, including representations of the various respective portions of the environment that produced the corresponding scattered portions of the laser beam to produce the R_1 ... R_N values.

In this embodiment, following execution of block **600**, block **610** directs the representation processing circuit **560** to process and assemble the radar data for analysis. In this regard, block **610** first directs the representation processing circuit to read the contents of the flight line sub-field **344** of the manual data sub-field **342** of each of the data structures stored as the data **302** in the memory device **52**, to identify all such data structures corresponding to the currently addressed flight line (addressed above at block **600**), having radar data stored in their radar beam field **360**. As with the laser data, In this embodiment the system **50** produces approximately **10,000** data structures containing radar data corresponding to locations approximately **1** meter apart along each flight line. Block **610** directs the representation processing circuit to sequentially address each such data structure, and to copy contents of the GPS sub-field **338** and the radar beam field **360** to a corresponding column of a table defined in the assembled data store **379** in the second memory device **329**. More particularly, in this embodiment each such column in the assembled data store **379** includes a GPS field containing GPS data of the form (x, y, z) representing the interpolated position at which the radar measurement represented by a particular corresponding data structure was produced, and includes a radar field which in turn includes **512** positions (rows) or entries, each including two bytes representing the I-channel and Q-channel data respectively stored in the radar beam field **360** of the particular data structure.

If desired, block **610** may further direct the representation processing circuit **560** to perform pre-processing on the contents of the assembled data store **379**. For example, in this embodiment, block **610** directs the representation processing circuit to perform a Fast Fourier Transform (FFT) on each column of data stored in the assembled data store **379**. The **512** (I, Q) byte pairs in each such column form a complex input vector of the form $f_K = I_K + iQ_K$ to be operated upon by the FFT, which produces and stores a corresponding set of

512 frequency-domain byte pairs, of the form (FR_K, FI_K) denoting the real and imaginary components of the FFT, over-writing the (I, Q) byte pairs of the column. In this regard, it will be recalled that the raw data **302** has been archived prior to commencement of the analysis routine **320**, and thus this over-writing does not result in loss of the original archived raw time domain data.

In the present embodiment, such pre-processing further includes identification and removal of any interferers present in the resulting FFT values. In this regard, interferers such as noise spikes may sometimes arise at particular frequencies. In this embodiment, to identify such interferers, for each N^{th} frequency line represented by each respective N^{th} one (**2** $\leq$ N $\leq$ **511**) of the **512** frequency-domain byte pairs (FR_N, FI_N) of a given column of the assembled data store **379**, block **610** directs the representation processing circuit **560** to compare the signal amplitude P_N represented by each such frequency-domain byte pair to the signal amplitudes P_{N-1}, P_{N+1} at neighboring frequency lines represented by neighboring frequency-domain byte pairs (FR_{N-1}, FI_{N-1}) and (FR_{N+1}, FI_{N+1}). If both $P_N \geq 2P_{N-1}$ and $P_N \geq 2P_{N+1}$, then it is concluded that P_N corresponds to a noise spike, and accordingly, P_N is reduced to $0.5(P_{N-1}+P_{N+1})$, and (FR_N, FI_N) are adjusted accordingly. For N=**1** (corresponding to baseband frequency) no such identification or removal need be performed as this frequency will be reset to zero (discussed below), and for N=**512**, the signal amplitude may simply be compared to that of N=**511**.

In addition, in the present embodiment such pre-processing further includes normalization of the spectrum represented by each column of the assembled data store **379**. To achieve this, for each addressed column of frequency-domain byte pairs (FR, FI), block **610** first directs the representation processing circuit **560** to effectively divide the time-domain values (I, Q) corresponding to the column contents (FR, FI) by a set of average time-

domain return values that are expected from a reference environment (in this embodiment a flat liquid surface), by performing an equivalent frequency-domain deconvolution from the column contents of an average spectrum or spread function for the reference environment.

In this regard, in the present embodiment, to obtain the spread function for the reference environment, the aircraft **100** is flown over calm, flat water at least once during the mission, during which time at least one radar measurement data structure (referred to as the spread function data structure) is generated in the same manner as described above in connection with block **510** of the measurement routine. A user of the system **50** actuates the user input device **90** to cause a special identifying notation to be stored in the measurement context field **336** of this spread function data structure, such as in the manual data sub-field **342** for example. Block **610** directs the representation processing circuit to locate the spread function data structure, apply a Fast Fourier Transform (FFT) to the (I, Q) pairs of the data structure, and to remove interferers from the corresponding frequency-domain byte pairs (SFR, SFI) as described above, yielding a set of **512** spread function byte pairs (SFR, SFI) which may then be used for normalization of all radar data obtained during the mission.

Once this set of spread function byte pairs has been obtained, block **610** directs the representation processing circuit **560** to convolve the contents (FR, FI) of each column of the assembled data store **379** with the spread function values (SFR, SFI) in the frequency domain, to yield normalized frequency-domain byte pairs (FR, FI).

To complete the normalization process, in this embodiment block **610** directs the representation processing circuit **560** to truncate the normalized frequency-domain byte pairs (FR, FI) by further convolving them with a

suitable window function in the frequency domain, which in this embodiment is a Kaiser window (K=**4**). Alternatively, other suitable windows may be substituted, such as a Hamming window (**0.48**cos(ωt)+**0.54**), for example.

In the present embodiment block **610** further directs the representation processing circuit **560** to set the (FR, FI) bytes in location **1** of each column of the assembled data store **379**, which correspond to baseband frequency (DC), equal to zero. In this regard, it will be recalled that the second signals **58** in the present embodiment were frequency-shifted by the radar reception system **68** from **300**±**100** MHz down to **0**±**100** MHz, and therefore contain a significant baseband (DC) component, which block **610** effectively removes.

Block **610** then directs the representation processing circuit **560** to perform an inverse Fast Fourier Transform (FFT^{-1}) on the **512** byte pairs stored in the presently addressed column of the assembled data store **379**, effectively converting such values back into time-domain byte pairs of the form (I, Q), which are over-written into the presently addressed column.

In addition, in the present embodiment block **610** further directs the representation processing circuit **560** to decompose the calibration signal from the (I, Q) byte pairs. It will be recalled that in the present embodiment, the calibration signal includes the **320** MHz sine-wave generated by the calibration signal generator **226** and down-shifted to **20** MHz by the frequency-shifter **227** shown in Figure **7**. Block **610** directs the processor circuit to compare the decomposed calibration signal data with stored digital data representing a **20** MHz reference sine wave, to determine whether any "drop-out", or in other words, a failure by the ADC **400** to take a sample, has occurred. It will be appreciated that such a drop-out will result in two successive samples of the decomposed calibration signal which are actually **4** ns apart in time, appearing in the sampled data as if they were only **2** ns

apart, resulting in a discontinuous vertical jump in the decomposed calibration signal. If any such drop-out is detected, block **610** directs the representation processing circuit to "pad" the data, by inserting an additional (I, Q) byte pair at the point of discontinuity of the calibration signal, identical to the (I, Q) byte pair immediately preceding the discontinuity. In addition, block **610** directs the representation processing circuit to monitor the decomposed calibration signal data for "stuck bits", or in other words, a malfunctioning of the ADC **400** resulting in a given bit position being always **1** or always **0**. If such stuck bit errors are detected, an alarm message is generated and displayed to a user of the representation processing circuit.

Block **610** directs the representation processing circuit to repeat the foregoing steps for each of the columns stored in the assembled data store **379**, until all such radar data corresponding to the currently addressed flight line has been pre-processed and assembled in the assembled data store **379** in the above manner. In addition to storing such values in the assembled data store **379**, block **610** directs the representation processing circuit to copy such values to a corresponding assembled data store **612** of the analyzed data region **605** of the memory device **52**.

Thus, following execution of block **610**, the assembled data store **379** contains approximately **10,000** columns of radar data, each successive column including a radar field including **512** (I, Q) byte pairs that have been pre-processed as described above, and a GPS field containing data indicating a respective successive interpolated position of the aircraft **100** at which the radar measurements represented by the contents of the radar field were obtained.

In this embodiment, block **620** configures the representation processing circuit to apply a migration algorithm to the data representing the second signals **58**

(or more particularly, to the data stored in the assembled data store **379**), to associate the data representing the second signals with particular locations of the environment.

In this regard, it will be appreciated that the system **50** of the present embodiment employs considerably longer radar wavelengths (on the order of one meter), and a considerably broader radar bandwidth (a frequency width of **66**% of its central frequency), than conventional radar systems (which typically employ a much narrower bandwidth surrounding a shorter central wavelength, on the order of **1** cm, **10** cm or **100** cm, for example). The wavelength ranges of the present embodiment provide numerous advantages over conventional systems, as the longer wavelengths used in the present embodiment may be used to obtain much deeper subterranean penetration for profiling of sub-surface features than conventional systems. For example, wavelengths shorter than **3** cm typically provide no ground penetration, and wavelengths as long as **30** cm typically do not penetrate further than **1** - **2** m even in exceptionally dry soil conditions, whereas the longer **1.0** - **1.5** m wavelengths employed in the present embodiment typically provide returns from depths of **10** m in normal soil. When coupled with the wide bandwidth employed in the present embodiment, such radar provides greater resolution than conventional radar systems, and is adequate to identify ground and foliage height with sufficient accuracy for the vast majority of applications. In addition, as the range from **0.75** m to **1.5** m is often reserved by governments for communications uses, there is typically very little noise in this wavelength region, which is advantageous for obtaining more sensitive measurements, and conversely, the power level and downward transmission direction of the incident radar beam **102** are not likely to cause undue interference in this wavelength range. However, the longer wavelength of the present embodiment results in greater beam divergence, typically about **5°** (a spot

size of **25** m produced from an altitude of **300** m AGL), in contrast with **1** - **2°** beam widths that are often achieved with conventional radar systems.

Conventional radar analysis systems typically include compression algorithms, to effectively decrease the spot size of the beam. However, such compression algorithms are typically not suitable for data produced in response to a beam width as great as **5°**.

Accordingly, in order to effectively decrease the spot size of the beam, and thereby increase measurement accuracy, in the present embodiment a migration algorithm is applied to the data in the assembled data store **379** produced in response to the second signals **58**. In this regard, although migration algorithms have previously existed in other technical fields, such as geophysics for example, migration algorithms have not been previously applied in the technical field of airborne radar measurements, which is one possible application of the present embodiment of the invention.

Effectively, the principle underlying the migration algorithm is as follows. From the point of view of the radar reception system **68** of the present embodiment, when a portion of the environment **104** scatters the incident radar beam to produce a scattered portion which is received at the radar reception system, the location in the radar beam field **360** at which the data representing the scattered portion is stored is indicative of the time at which the scattered portion was received, and is therefore indicative of the scalar distance from the aircraft **100** to the portion of the environment that produced the received scattered portion of the radar beam. However, the radar reception system in the present embodiment does not measure the angle or direction to the corresponding portion of the environment which scattered the received portion of the radar beam. From an analytical point of view, therefore, in this embodiment it is as if all received scattered portions were

received from directly below the aircraft **100**, when in fact they were not. A given fixed point of the environment, such as a target spot on ground level of the environment, for example, will initially be a first scalar distance away from the aircraft **100**, and this distance decreases as the aircraft approaches the fixed point. As the aircraft flies directly over the fixed point, the scalar distance between the aircraft and the point will be a minimum, and as the aircraft passes over the fixed point and moves away from it, the scalar distance will increase. Geometrically, the scalar distance of the fixed point from the aircraft, plotted against horizontal position of the aircraft, will map out a hyperbola.

By way of example, for a particular application, the aircraft **100** may fly flight lines of **10,000** meters each, with **10,000** corresponding data structures containing radar data produced and stored as described above in connection with block **510** of the measurement routine, and with corresponding data structures being produced and stored in the assembled data store **379** as described above in connection with block **610**, each such data structure being produced at a **1**m interval as the aircraft **100** flies at **75** m/s ground speed. In most cases, it may be assumed that each flight line is flown in a straight line with respect to latitude and longitude, at constant ground speed, although the altitude Z_{GPS} of the aircraft **100** may vary relative to the geoid, either intentionally or due to updrafts or downdrafts. In any event, the aircraft's position at any given location at which a corresponding set of radar data was obtained may be expressed as (x, y, z).

Similarly, any given fixed point of the environment **104** along the flight line (i.e., in the vertical plane defined beneath the aircraft **100** as it flies along the flight line) may be described by coordinates (x_{FP}, y_{FP}, z_{FP}). At any one of the **10,000** interpolated aircraft positions (x, y, z) at which radar data of the

environment was obtained, the scalar distance from the aircraft **100** to the fixed point (x_{FP}, y_{FP}, z_{FP}) will be:

$$d = \sqrt{(x_{FP} - x)^2 + (y_{FP} - y)^2 + (z_{FP} - z)^2} \quad \textbf{(4)}$$

It therefore follows from geometry, and from equations (**3**) and (**4**), that if a scattered portion of the incident radar beam scattered by the fixed point (x_{FP}, y_{FP}, z_{FP}) is received by the radar reception system **68** at the k^{th} aircraft position (x_K, y_K, z_K) along the flight line, then the position (row) P in the k^{th} data structure representing such a scattered portion is (rounded to the nearest natural number):

$$P_K = \frac{\frac{2d_K}{c} - t_{DEL}}{t_{SAM}} = \frac{\frac{2}{c}\sqrt{(x_{FP} - x_K)^2 + (y_{FP} - y_K)^2 + (z_{FP} - z_K)^2} - t_{DEL}}{t_{SAM}} \quad \textbf{(5)}$$

wherein

P_K = the position value (**1** $\leq$ P $\leq$ **512**) representing the position (row number) in the k^{th} successive column of radar data stored in the assembled data store **379** (obtained by the aircraft **100** at location (x_K, y_K, z_K)) containing data representing a scattered portion (if any) scattered by the fixed point (x_{FP}, y_{FP}, z_{FP}) of the environment **104**;

(x_K, y_K, z_K) = the interpolated displacement of the aircraft **100** at the location of the k^{th} radar measurement, in meters relative to a reference point (z_K is relative to the geoid), obtained from the GPS field of the k^{th} column of the assembled data store;

(x_{FP}, y_{FP}, z_{FP}) = the displacement of the fixed point of the environment **104** that is of current interest, in meters relative to a reference point;

c = the speed of light in meters per second;

t_{DEL} = the time delay in seconds following the transmission of the incident radar beam **102** prior to commencing sampling and storing data representing the second signals **58** (in this embodiment, t_{DEL} = **1.2** x **10**$^{-6}$ s);

t_{SAM} = the sampling period in seconds between successive samples of the second signals **58** (in this embodiment, t_{SAM} = **2.0** x **10**$^{-9}$ s).

In addition to data representing radar scattering by the fixed point (x_{FP}, y_{FP}, z_{FP}), the value stored in the P^{th} location of the k^{th} radar data set may have also been produced in response to scattering by other portions of the environment, which produce a source of random noise. On average, however, if, for a particular fixed point (x_{FP}, y_{FP}, z_{FP}) of the environment, a position value P_j is calculated for all of the **10,000** data sets (or at least, for all data sets for which **1** $\leq$ P $\leq$ **512**, which therefore contain data corresponding to the fixed point (x_{FP}, y_{FP}, z_{FP})), and the contents of the position fields P_j of each such radar data set are summed or integrated, then if the fixed point (x_{FP}, y_{FP}, z_{FP}) is a significant reflector, such as a point on the ground for example, then the resulting sum will be significant. Conversely, if the fixed point is not a significant reflector (such as a point in mid-air, for example) then the data stored in the locations P_j of the radar data sets will represent merely background noise from other locations of the environment, which does not add in phase on average, and therefore, the resulting sum will be low or zero.

Accordingly, in this embodiment, block **620** directs the representation processing circuit to apply a migration algorithm to the radar data stored in the assembled data store **379**. More particularly, block **620** directs the representation processing circuit to define a set of fixed points of the environment, such as the fixed point (x_{FP}, y_{FP}, z_{FP}) discussed above. More particularly, in this embodiment the fixed points of interest include a two-dimensional array of fixed points, spaced horizontally at one meter intervals along the currently addressed **10** km flight line, and spaced vertically at one meter intervals from **120** m above the geoid to **30** m below the geoid (it will be recalled that in this embodiment the aircraft **100** flies each flight line approximately **300** m above the geoid). Thus, in this embodiment the representation processing circuit defines **10,000** x **150** = **1,500,000** fixed points of the environment, for consideration. For each such fixed point, block **620** directs the representation processing circuit to calculate a set of position values P_j as discussed above, each successive position value P_j representing a position (row) in a respective successive one of the **10,000** radar data sets stored in the assembled data store **379**, although alternatively, such position values P_j may be pre-calculated and stored in look-up tables, if desired. (It is noted that for any particular fixed point of the environment, it is not necessary to calculate P_j for the majority of measurement locations of the aircraft along the flight line, due to the limited beam width of the incident radar beam, and also because P_j does not exist in the required range **1** $\leq P_j \leq$ **512** for many of the **10,000** radar data sets, as the measurement location (x, y, z) of the aircraft **100** for many of the radar measurements is too far away from a particular fixed point (x_{FP}, y_{FP}, z_{FP}) for data from the fixed point to have been received at the aircraft during the **512**-sample measurement window. Typically, for a particular fixed point (x_{FP}, y_{FP}, z_{FP}), it is not necessary to calculate P_j for any measurement locations (x, y, z) of the aircraft in respect of

which the angle formed by a vertical line through the fixed point and a line joining the fixed point to the measurement location is more than **15°**).

Block **620** then directs the representation processing circuit to calculate a sum $\sum_P R$ of the contents of the radar data stored in the locations P_j, or more particularly a sum of the magnitudes of the complex vectors $f_P = I_P + iQ_P$ represented by the (I, Q) byte pairs stored in each of the locations P_j. Block **620** further directs the representation processing circuit to store the co-ordinates (x_{FP}, y_{FP}, z_{FP}) identifying the fixed point, along with the resulting sum $\sum_P R_{FP}$ corresponding to the co-ordinates, in the migrated data store **381** in the second memory device **329**. In addition to storing such values in the migrated data store **381**, block **620** directs the representation processing circuit to copy such values to a corresponding migrated data store **622** of the analyzed data region **605** of the memory device **52**.

In this embodiment, block **630** then directs the representation processing circuit **560** to identify a height of a terrain surface of the environment. In this regard, the ground level of the environment (either soil or surface liquid, if present) will typically scatter the incident radar beam **102** with considerably greater intensity than any other portion of the environment. Accordingly, in this embodiment, block **630** directs the representation processing circuit to successively address each set of migrated data corresponding to a given vertical column of fixed points of the environment **104** (in other words, each vertical column of fixed points is for a fixed (x_{FP}, y_{FP}), and includes **150** different values z_{FP} spaced **1** m apart ranging from **+120** m to **-30** m relative to the geoid, along with the **150** corresponding radar sum values $\sum_P R_{FP}$ for the **150** points z_{FP}. Block **630** directs the representation processing circuit to identify the fixed point z_{FPG} whose corresponding sum value $\sum_P R_{FP}$ has the greatest magnitude, and to store a corresponding set of coordinates (x_{FP}, y_{FP}, z_{FPG}) in the ground return height store **374**. Block **630** directs the

representation processing circuit to continue identifying and storing ground return heights z_{FPG} in this manner until **10**,**000** such ground return heights have been identified and stored in the ground return height store **374**, one for each one-meter measurement interval at each location (x_{FP}, y_{FP}) along the currently addressed flight line. Block **630** further directs the representation processing circuit to copy such ground return data to a ground return height store **632** in the memory device **52**.

In this embodiment, block **630** further directs the representation processing circuit **560** to identify a relative foliage height of the environment. More particularly, in this embodiment, for each (x, y) location along the currently addressed flight line, block **630** directs the representation processing circuit to subtract the corresponding ground return height value z_{FPG} stored in the ground return height store **374**, from the corresponding first return R**1** value stored in the first return height store **372**, to identify a height of foliage of the environment relative to the ground level of the environment at location (x, y). Block **630** directs the representation processing circuit to store the resulting relative foliage height values z_{RFH} in the foliage height store **375**, along with the corresponding coordinates (x, y) to which the respective foliage height values relate. In this regard, it is noted that the use of laser data representing absolute foliage height (stored in the first return height store **372**) is typically more reliable than corresponding radar data representing absolute foliage height, as the latter typically has a low signal-to-noise ratio (such as **3** dB for example). Conversely, however, radar data representing ground height has a significantly higher signal-to-noise ratio than radar data representing foliage, and therefore provides a reliable estimate of ground height, whereas laser data representing ground height usually cannot be obtained in areas of thick foliage. Thus, the combination of laser and radar data as described above results in a more reliable determination of relative foliage height than either laser data alone or radar data alone could provide.

In this embodiment, in addition to storing such values in the foliage height store **375**, block **630** directs the representation processing circuit to copy such values to a corresponding foliage height store **634** of the analyzed data region **605** of the memory device **52**.

Alternatively, if desired, rather than using both laser and radar data to identify relative foliage height, block **630** may direct the representation processing circuit to use radar data alone to identify the relative foliage height. In this regard, an alternative block **630** may direct the representation processing circuit to produce a radar first return height store (not shown) in response to the contents of the migrated data store **381**, by identifying a first return height z_{FP} for each location (x_{FP}, y_{FP}) having a corresponding sum value $\sum_P R_{FP}$ significantly greater than an expected noise value (for example, at least twice as great as noise). The alternative block **630** may then direct the representation processing circuit to subtract the corresponding ground return height value z_{FPG} from the first return height z_{FP} and to store the resulting difference in the foliage height store **375**.

Additionally, if desired, block **630** may further direct the representation processing circuit **560** to identify features of the environment below the terrain surface. For example, in this embodiment block **630** direct the representation processing circuit to read the contents of the migrated data store **381**, and if, for any given measurement location (x_{FP}, y_{FP}), any sum value (or values) $\sum_P R_{FP}$ greater than an expected noise value exists, corresponding to a return height z_{FP} less than the ground return height z_{FPG} for that location (i.e., underground), block **630** directs the representation processing circuit to store the co-ordinates (x_{FP}, y_{FP}, z_{FP}) for all such points in the subterranean data store **378**. In this embodiment, the corresponding sum value $\sum_P R_{FP}$ is also stored in association with each such set of coordinates, and such coordinates

and sum values are also copied to a corresponding subterranean data store **636** in the memory device **52**.

Block **640** then directs the representation processing circuit **560** to determine whether all flight lines for the mission have been processed as described above. If not, block **640** directs the representation processing circuit to continue processing data corresponding to the next successive flight line flown by the aircraft **100** over the environment **104**, as described above in connection with blocks **600** - **630**, until data corresponding to all flight lines have been processed and stored in the above manner.

In addition, in this embodiment, when all flight lines have been processed, block **640** directs the representation processing circuit **560** to repeat blocks **600** through **630** in relation to contents of the data **302** obtained during the course of the aircraft **100**'s flight across the various tie lines over the environment **104**, which in this embodiment are flown substantially perpendicular to the flight lines. The representation processing circuit is directed to produce and store analogous data in the tie lines region **383** of the second memory device **329**, which in this embodiment includes respective stores (not shown) corresponding to the various other stores of the second memory device **329** discussed above in connection with blocks **600** through **630**. As with flight line data, such tie line data is also copied to the analyzed data region **605** of the memory device **52**. In this regard, it has been found that such tie line data is potentially useful for a number of purposes, including reduction of errors in production of contours from the flight line data, for example. Also, if desired, the tie line data corresponding to locations intersecting the flight lines may be compared to the corresponding flight line data for the point of intersection, to produce and store error correction data. Such error data may then be further analyzed to identify any possible systematic errors present in the flight line data, in order to correct or

compensate the flight line data for such errors, if desired. Alternatively, however, the tie lines may be omitted or ignored, if desired.

In this embodiment, block **650** then directs the representation processing circuit **560** to format the contents of the first return height store **372**, the ground return height store **374** and the foliage height store **375**, and to store the resulting formatted data in the first return grid **373**, the ground grid store **376** and the foliage grid store **377** respectively, and also in corresponding grid stores **654**, **656** and **658** in the memory device **52**. In this embodiment, block **650** further directs the representation processing circuit to produce and store corresponding formatted tie line ground grid and tie line foliage grid data in the tie lines region **383** and a corresponding tie lines region **652** in the memory device **52**. In this embodiment, each such grid is formatted as a **2**-D matrix, with the relevant x and y coordinates serving as indices defining the locations of the respective corresponding z values, as such a format is useful for many contouring algorithms. Alternatively, however, other formats may be substituted.

Referring to Figures **8a**, **8b**, **12**, **13** and **14**, block **660** then directs the representation processing circuit **560** to determine whether user input requesting display of a representation of the environment **104** along a specified flight line has been received. If so, block **662** directs the representation processing circuit **560** to produce and display a flight line representation, such as that shown at **664** in Figure **13** for example. More particularly, in this embodiment the flight line representation **664** includes a relative foliage height field **666**, a ground altitude field **668** and a slope field **670**.

In this embodiment, to produce the flight line representation **664**, block **662** directs the representation processing circuit **560** to identify contents of the

ground grid store **376** and the foliage grid store **377** corresponding to the user-specified flight line. In response to such data, block **662** directs the representation processing circuit to display appropriate scaling information adjacent the ground altitude and relative foliage height fields **668** and **666**. In this embodiment, block **662** then directs the representation processing circuit to apply a fitting algorithm, such as a least-squares fitting algorithm for example, to the ground height values z_{FPG} stored in the ground grid store **376** corresponding to respective successive locations (x_{FP}, y_{FP}) along the current flight line, and to plot a resulting best-fit curve **672** in the ground altitude field **668**. In a similar manner, block **662** also directs the representation processing circuit to produce a best-fit curve **674** and to display it in the relative foliage height field **666**, in response to the contents of the foliage grid store **377** corresponding to the current flight line. Alternatively, however, rather than applying a best-fit curve, the relevant contents of the ground grid store **376** and foliage grid store **377** may simply be plotted as successive data points in the fields **666** and **668**, if desired.

In addition, in the present embodiment, block **662** directs the representation processing circuit to identify a slope of a terrain surface of the environment **104**. More particularly, block **662** directs the representation processing circuit to calculate ground slope information, and to display a representation of such information in the slope field **670** of the flight line representation **664**. In this embodiment, block **662** directs the representation processing circuit to calculate such slope information in response to the ground grid store data (x_{FP}, y_{FP}, z_{FPG}) corresponding to the specified flight line, at N intervals d m apart (in this embodiment, d = **30** m), by calculating a slope value $\theta=TAN^{-1}[(z_{FPG(N)}-z_{FPG(N-1)})/d]$. Alternatively, however, the slope may be calculated in other ways and/or at different intervals, if desired. In this embodiment, block **662** directs the representation processing circuit to display the resulting slope

values as a bar graph in the slope field **670** of the flight line representation **664**.

Alternatively, other types of flight line representations may be substituted if desired. For example, referring to Figures **8a**, **8b**, **12**, **13** and **14**, a segment of a representation of a subterranean portion of the environment **104** is shown generally at **680** in Figure **14**. In this embodiment, the representation **680** may be produced by the representation processing circuit **560** in response to receipt of a user-specified command requesting such a representation. The segment of the representation **680** shown in Figure **14** corresponds to a much shorter segment of the environment **104** (approximately several meters across) than the flight line representation **664** shown in Figure **13**. To produce such a representation, block **662** directs the representation processing circuit to display a greyscale pixel for each data point (x_{FP}, y_{FP}, z_{FP}, $\Sigma_P R_F$) stored in the subterranean data store **378**, the opacity of which is proportional to the sum value$\Sigma_P R_F$. In the exemplary segment **680**, several hump-shaped irregularities **682**, **684** and **686** may be observed, which in this embodiment are human graves beneath the surface of the environment **104**.

If desired, block **662** may also direct the representation processing circuit to store the resulting flight line representation **664** or **680** in the analyzed data region **605** of the memory device **52**.

Referring to Figures **8a**, **8b**, **12**, **15** and **16**, following execution of block **662**, or alternatively if no user input requesting a flight line representation is detected, block **664** directs the representation processing circuit to determine whether user input requesting a contour display of the environment **104** has been received.

If so, block **692** directs the representation processing circuit **560** to produce a contour representation of the environment. More particularly, in this

embodiment block **692** directs the representation processing circuit to produce a digital elevation model of the environment. To achieve this, in this embodiment block **692** directs the representation processing circuit to execute the contouring routine **325**, which in this embodiment is the ANUDEM contouring software, to produce a digital elevation model in response to the entire contents of the ground grid store **376**. In this embodiment, in order to reduce interpolation errors, block **692** directs the contouring routine to produce the digital elevation model in response to not only the contents of the ground grid store **376**, but also in response to the contents of the tie line ground grid store (not shown) in the tie lines region **383** of the second memory device **329**. After directing the representation processing circuit to produce such a digital elevation model, the contouring routine **325** directs the representation processing circuit to display a representation of the digital elevation model, such as a two-dimensional contour representation **694** of the environment **104** as shown in Figure **15**, or a three-dimensional contour representation shown generally at **696** in Figure **16**, for example.

Alternatively, or in addition, other contour representations of the environment may be produced, such as foliage height representations or subterranean feature representations produced in response to contents of the foliage grid store **377** or the subterranean data store **378**, for example. If desired, such contour representations may be produced separately, or together with the ground altitude contour representations such as those shown in Figures **15** and **16**, superimposed thereover, for example.

Similarly, variations of any such contour representations may also be substituted. For example, break lines, or in other words, known reference features of the environment **104** whose positional coordinates are known, may be input into the contouring routine **325** for calibration purposes. Or, as a further example, planimetric features, such as labels identifying villages,

roads, rivers, drainage features and the like may be added to a contour representation to produce a full digital elevation map of the environment **104**.

Similarly, if desired, referring back to Figures **2**, **8a**, **8b**, **11** and **12**, the camera **92** shown in Figure **2** may be used to obtain visual images of the environment **104**. For example, block **460** of the measurement routine **308** shown in Figure **9** may be modified to additionally transmit a triggering signal to the camera **92** at a pre-defined interval, to cause the camera to produce digital data signals representing a visual image of the environment **104** beneath the aircraft **100** as it flies along a given flight line. Modified block **460** further directs the processor circuit **54** receive such signals via the I/O system **390**, and to store corresponding image data in the memory device **52**. For example, the processor circuit may be directed to store the image data in a camera field **698** of the data structure **334** in the second memory device **329**, and to then copy the data structure to the memory device **52** as previously described. If desired, other representations of the environment, such as the contour representations described above for example, may be superimposed over the stored visual images of the environment, to produce a digital elevation map of the environment.

The analysis routine **320** is then ended.

ALTERNATIVES

Dual UWB Bands

Although the foregoing embodiment illustrates use of a **200-400** MHz ultra-wide band radar frequency range, alternatively, other frequency ranges may be substituted or added.

For example, referring to Figures **2**, **6** and **17**, a radar transmission system according to a third embodiment of the invention is shown generally at **700** in

Figure **17**. In this embodiment, the radar transmission system **700** alternates between **200-400** MHz UWB radar pulses and **400-600** MHz UWB radar pulses. In this regard, the latter higher-frequency UWB range yields sharper spot coverage and therefore sharper resolution. At the same time, however, the former lower-frequency UWB range yields deeper penetration through foliage and other solid objects. Alternatively, for some applications it may be desirable to produce and store data produced in response to both these frequency ranges, to obtain the benefits of each.

In this embodiment, the radar transmission system **700** includes the UWB transmitter **144** shown in Figure **6**. In this embodiment, however, the UWB transmitter **144** is in communication with a first power combiner **702**, which in turn is in communication with a transmission antenna system **704**, which in this embodiment is capable of transmitting radar pulses having frequencies between **200** MHz and **600** MHz.

In this embodiment the radar transmission system **700** further includes first and second higher frequency UWB transmitters **706** and **708**, each of which is in communication with the central processing system **60** for receiving a triggering signal therefrom. In this embodiment, each of the higher frequency UWB transmitters is operable to transmit a unipolar impulse signal having a duration of approximately **2** ns and a voltage of **10** kV to the transmission antenna system **704**, to cause the antenna system to produce and tune a **2** ns electromagnetic radar pulse over an ultra-wide band frequency range between **400** MHz and **600** MHz (the **2** ns duration corresponds to a single cycle at the center frequency of **500** MHz).

A delay device **710** is interposed between the first higher frequency UWB transmitter **708** and the CPS **60**. More particularly, in this embodiment the delay device includes a **50**-ohm impedance delay cable of approximately **0.4**

m in length, through which a triggering signal received from the CPS **60** travels at a speed of approximately **2**c/**3**. Thus, in this embodiment the delay device **710** delays the arrival of the triggering signal at the second higher frequency UWB transmitter **708** for an additional **2** ns (one cycle of the center frequency of **500** MHz of the transmitter **708**) following the arrival of the triggering signal at the first higher frequency UWB transmitter **706**.

The higher frequency UWB transmitters **706** and **708** are both in communication with a second power combiner **712**, which receives the unipolar impulse signals produced by the first and second higher frequency UWB transmitters **706** and **708** and combines them onto a single signal line, which forwards the combined impulse signals, corresponding to two cycles at the **500** MHz center frequency, to the first combiner **702**.

The first combiner **702** receives the **400** - **600** MHz combined impulse signals from the second combiner **712**, and also receives a unipolar impulse signal from the UWB transmitter **144** operable to cause the transmission antenna system to produce and tune a **200** MHz - **400** MHz radar pulse.

Referring back to Figures **7**, **8a** and **8b**, in this embodiment the oscillator **260** shown in Figure **7** includes a **300** MHz oscillator and additionally includes a **500** MHz oscillator, along with an SPDT switch (not shown) for switching between the two frequencies. The SPDT switch includes a monitoring connection in communication with the I/O system **390** of the CPS **60**, for providing a signal indicative of the switch position. In addition, if desired, the calibration signal generator **226** may include first and second calibration signal generators switchable between two calibration signal frequencies, such as **320** MHz and **520** MHz for example.

Referring to Figures **7**, **8a**, **8b** and **17**, in operation, as with the main embodiment described above, a radar pulse is produced **75** times per second.

However, in this embodiment, to produce every odd-numbered radar pulse, the processor circuit **54** transmits a triggering signal to the first higher-frequency UWB transmitter **706**, which is also received at the second higher-frequency UWB transmitter **708** via the delay device **710**. The UWB transmitters **706** and **708** each produce a unipolar impulse signal operable to drive the transmission antenna system **704** to produce a **2** ns radar pulse at **400** MHz - **600** MHz, with the unipolar impulse signal produced by the second UWB transmitter **708** being delayed by **2** ns (one cycle at **500** MHz) relative to that produced by the first UWB transmitter **706**. Such signals are combined by the combiner **712** which transmits the combined signal via the combiner **702** to the transmission antenna system **704**, which produces a radar pulse at frequencies of **500±100** MHz, having a duration of **4** ns (two cycles at **500** MHz). The processor circuit **54** also transmits a switching signal to the oscillator **260**, to cause the oscillator to transmit a **500** MHz mixing frequency signal to the frequency shifter **227**, to effectively down-shift the resulting **500±100** MHz second signals **58** to **0±100** MHz (the same down-shifted frequency range as the **300±100** MHz second signals **58** of the main embodiment described above). If desired, the processor circuit may also transmit a switching signal to the calibration signal generator **226** to cause it to insert a **520** MHz rather than **320** MHz calibration signal into the second signals **58**.

Similarly, to produce every even-numbered radar pulse, the processor circuit **54** transmits a triggering signal to the UWB transmitter **144** to produce a **300±100** MHz radar pulse, and transmits a triggering signal to the switch of the oscillator **260** to cause the oscillator to transmit a **300** MHz mixing frequency to the frequency-shifter **227** (as well as an additional triggering signal to the calibration signal generator to cause it to produce a **320** MHz calibration signal).

Processing, storage and analysis of such radar data proceeds as above, with the exception that each data structure **334** further includes a frequency sub-field **714** of the measurement context field **336**. The processor circuit **54** is configured to store in the frequency sub-field **714**, as the measurement context information, a frequency value indicative of a frequency of the radar beam. More particularly, in this embodiment the processor circuit stores a bit in the frequency sub-field **714** in response to the monitoring signal received from the switch of the oscillator **260**, indicative of whether the oscillator is producing a **300** MHz or a **500** MHz mixing signal (effectively indicating whether the frequency of the radar pulse, in response to which the radar data stored in the data structure **334** were produced, was **300±100** MHz or **500±100** MHz).

Radar Transceiving System

Referring to Figures **6**, **7** and **18**, although the radar transmission system **66** and the radar reception system **68** were described above as including separate respective antenna systems **108** and **110**, alternatively, the transmission antenna system and the reception antenna system may include a common transceiving antenna system, for both transmission and reception, if desired.

For example, a radar transceiving system according to a fourth embodiment of the invention is shown generally at **720** in Figure **18**. In this embodiment, the transceiving system **720** includes an antenna system **722** and a delay device **724**, which in this embodiment are similar to the antenna system **110** and delay device **172** of the radar reception system **68** shown in Figure **7**.

In this embodiment, the transceiving system **720** further includes a transmit/receive switch **726**, in communication with the central processing system **60**. In this embodiment, the transmit/receive switch **726** includes

suppression circuitry, sufficient to suppress signals produced by the antenna system **722** in response to leakage (i.e. inadvertent direct transmission from one antenna to another) of a portion of a transmitted radar pulse.

In the present embodiment, the transmit/receive switch **726** is in communication with the UWB transmitter **144** shown in Figure **6**, and with the blanker **190** and receiver **150** shown in Figure **7**. The transmit/receive switch is controllable by the processor circuit **54** to alternately transmit without receiving (or more particularly, to transmit unipolar impulse signals produced by the UWB transmitter **144** to the antenna system **722** while suppressing signals produced by the antenna system **722**), and conversely, to receive without transmitting (or more particularly, to transmit signals produced by the antenna system **722** in response to received electromagnetic radiation to the blanker **190** and receiver **150**, while suppressing signals produced by the UWB transmitter **144**.)

In embodiments wherein the antennae are distributed over a distance (mounted along the underneath of the wings of the aircraft **100** from wing-tip to wing-tip for example), this provides for a considerably smaller radar spot projection on the environment **104**, thereby effectively improving resolution. In some embodiments this may obviate the desirability of migrating the radar data as described above.

Arbitration

If desired, the laser data may be used to arbitrate the radar data. For example, the representation processing circuit **560** may be configured to examine the radar and laser height estimates, and to determine if local terrain slope caused any degradation in radar accuracy. If so, the representation processing circuit may be configured to find the nearest points in which the laser system was able to see the ground and interpolate a correction function.

Liquid

The representation processing circuit **560** may be additionally configured to identify surface liquid of the environment **104**. In this regard, water has a significantly higher dielectric constant, and therefore significantly higher radar reflectivity, than dry ground. Accordingly, the representation processing circuit may be configured to compare the sum values stored in the migrated data store **381** to a pre-determined threshold value, to determine whether each respective fixed point corresponding to each such sum value is likely to represent surface water of the environment.

More generally, while specific embodiments of the invention have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.